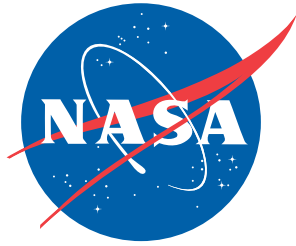


NASA/TM-2010-216729/Volume II  
NESC-RP-08-75



# NASA Aerospace Flight Battery Program

## *Wet Life of Nickel-Hydrogen (Ni-H<sub>2</sub>) Batteries*

*David S. Jung and Leonine S. Lee*  
*Goddard Space Flight Center, Greenbelt, Maryland*

*Michelle A. Manzo*  
*Glenn Research Center, Cleveland, Ohio*

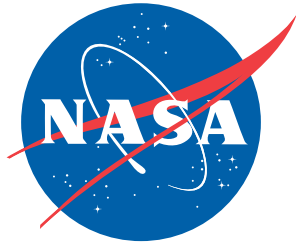
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August 2010

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# **NASA Aerospace Flight Battery Program**

## **Part 3: Wet Life of Nickel-Hydrogen (Ni-H<sub>2</sub>) Batteries**

### **Volume II: Appendices**


February 18, 2010

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## **Appendix A. Electrical Testing and Destructive Physical Analysis of Nickel Hydrogen Cells with Various Storage Histories**

**Work was performed under Contract Number NNL07AM00T**


### **Electrical Testing and Destructive Physical Analysis of Nickel-Hydrogen Cells with Various Storage Histories**

**Hari Vaidynathan, Lockheed Martin/Comsat Technical Services**

#### **1.0. Summary**

The effect of wet life on the performance of nickel-hydrogen cells was investigated in this study that focused on electrical characterization and destructive physical analysis. The cells for this study were carefully selected. While the storage histories were not fully documented, the majority of the cells were in cold storage after the initial acceptance testing. The 26 cells used in this study belonged to past programs such as Terra, ISS, US Government, Commercial and HST. Electrical characterization consisted of stabilizing the cells at 0°C, 10°C and 20°C and measuring the charge voltage profiles and discharge capacity, charge retention, and voltage rise from the discharged condition and reversal voltage. For the cells subjected to Destructive Physical Analysis (DPA) at Lockheed Martin/Comsat Technical Services, the fill tube of the cell was then cut open to determine the presence of gas. Then, the cell was dissected to extract the electrode stack and examine the condition of the components including structural features, contaminants, and workmanship. Having finished the physical measurements the positive, negative, separator and electrolyte were analyzed for their properties such as positive active material composition, loading and coefficient of utilization, positive swelling and blistering, negative plate polarization, separator absorbency, electrolyte concentration, content and distribution. The highlights of the results were:

1. The capacity of the cells was not impacted by long wet life as shown by:
  - 10 years wet life 120 Ah commercial cell
  - 13 years wet life 81 Ah Space Station cells
  - 12-year-old 50 Ah Terra cells
  - 10 years wet life 90-9 US Govt. cells
  - 4 years dry plus 8 years wet life HST cells
  - 10 years wet life 160 Ah aqua cells
2. Seven cells having wet life > 7 years showed a second plateau.
3. Reversal voltage and gas analysis showed that nickel precharge is maintained.

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4. There is no obvious correlation between the number and size of blisters on the positive plates and the length of time the cells were stored. Coefficient of positive material utilization is unchanged.
6. Cells stored under controlled conditions (discharged and at  $0 \pm 5^{\circ}\text{C}$ , for up to 13 years, maintain performance and nickel precharge.

COMSAT Battery Laboratories received 26 nickel-hydrogen cells for analysis. All of the cells were characterized for their capacity at  $0^{\circ}\text{C}$ ,  $10^{\circ}\text{C}$  and  $20^{\circ}\text{C}$ , charge retention, reversal voltage, pulse discharge and initial voltage rise. After electrical characterization 11 cells were chosen for destructive physical analysis at COMSAT and 11 cells were shipped to The Aerospace Corporation.

## 2.0. Electrical Characterization

All the cells were subjected to capacity determination cycles at  $0^{\circ}$ ,  $10^{\circ}$  and  $20^{\circ}\text{C}$ , 72-hour charge retention at  $10^{\circ}\text{C}$  and reversal at  $20^{\circ}\text{C}$  and voltage rise in the discharged state. Table 1 shows the capacity of the cells at  $10^{\circ}\text{C}$ , low voltage capacity, charge retention, reversal voltage and the voltage rise after a resistor drain to 10 mV.

All the cells met their rated capacity and there was no anomalous behavior. There were no clear trends in the electrical behavior of the 26 cells as a function of wet life. However, there were some program specific trends as detailed in the following paragraphs.





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**Table 1. Performance Data**


Cell Type	Activation Date	S/N	10 °C CAPACITY DATA				reversal voltage	Voltage rise after 1 hr*
			to 1 V (Ah)	2nd plateau (%)	resistor (Ah)	Charge Retention (%)		
Terra,50 Ah	Jan-1995	122(3.5")	66.9	NA	1.1	90.3	-0.28	0.095
Terra,50Ah	Jan-1996	262(3.5")	64.7	NA	1.3	90.5	-0.29	0.084
ISS,81Ah	Oct-1994	224(3.5")	100.5	5.5	8.0	85.9	-1.43	0.134
ISS,81Ah	Apr-1995	306(3.5")	104.9	5.5	2.3	87.6	-0.78	0.121
ISS,81Ah	Oct-1996	501(3.5")	109.0	2.2	1.1	84.7	-0.37	0.165
ISS,81Ah	Jul-1997	972(3.5")	103.6	NA	1.4	88.8	-0.31	0.110
ISS,81Ah	Dec-1998	1728(3.5")	100.6	NA	3.5	89.8	-0.33	0.091
ISS,81Ah	Jan-2000	2170(3.5")	105.1	NA	1.2	88.9	-0.32	0.086
ISS,81Ah	Oct-2001	2188(3.5")	101.7	NA	1.2	88.9	-0.32	0.134
ISS,81Ah	Aug-2002	2517(3.5")	100.0	NA	1.0	88.5	-0.3	0.095
ISS,81Ah	Jun-2004	2932(3.5")	106.0	NA	1.4	88.6	-0.31	0.084
ISS,81Ah	Jun-2004	2933(3.5")	105.6	NA	1.1	88.7	-0.31	0.105
US Govt,90Ah	Mar-1997	102(3.5")	103.3	NA	0.6	87.2	-0.38	0.080
US Govt,90Ah	Mar-1997	165(3.5")	102.0	NA	0.7	87.3	-0.36	0.078
HST,90Ah	Aug-2000	605(3.5")	94.7	9.2	3.8	82.2	-1.52	0.061
HST,90Ah	Aug-2000	718(3.5")	95.1	9.1	3.5	84.6	-1.51	0.080
Comm.,120Ah	Apr-1997	1038(4.5")	153.2	NA	1.5	87.9	-0.41	0.063
Comm.,120Ah	May-1997	1052(4.5")	147.9	4.3	7.2	86.7	-1.53	0.060
Comm.,120Ah	Aug-1997	1238(4.5")	151.2	NA	1.7	87.3	-0.42	0.089
Comm.,120Ah	Aug-1999	1997(4.5")	139.9	NA	19.1	85.1	-1.23	0.072
Comm.,120Ah	Feb-2000	2204(4.5")	146.1	NA	1.3	87.3	-0.36	0.108
Comm.,120Ah	Feb-2004	2749(4.5")	139.8	NA	1.0	87.3	-0.33	0.091
Comm.,120Ah	Aug-2006	2925(4.5")	143.4	NA	3.1	87.1	-0.32	0.130
Aqua, 160 Ah	Nov-1997	5(4.5")	200.8	NA	3.1	85.5	-0.39	0.018
Aqua, 160 Ah	Nov-1997	89(4.5")	200.8	NA	3.4	84.2	-0.4	0.016
Aqua, 160 Ah	Nov-1997	15(4.5")	193.6	NA	1.8	87.7	-0.33	0.015

\* after resistor drain to 10 mV

### 2.1. Capacity

The capacity of the cells was not impacted by long wet life as shown by the results for the capacity measurements shown in Table 1 for cells with the following storage histories:

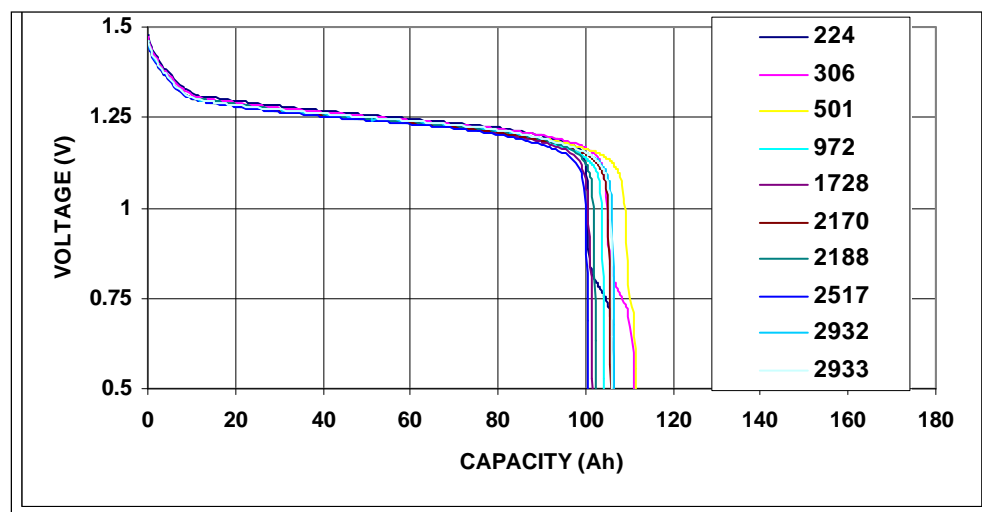
- 10 years wet life 120 Ah commercial cell
- 13 years wet life 81 Ah Space Station cells
- 12-year-old 50 Ah Terra cells
- 10 years wet life 90-9 US Govt. cells
- 4 years dry plus 8 years wet life HST cells
- 10 years wet life 160 Ah aqua cells

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All cells exhibited capacity greater than their rated capacity. Values ranged from 5% to 34% higher than rated capacity. There was no clear correlation between the value of the rated capacity and the wet life stand time.

## 2.2. Second Plateau


Nickel-hydrogen cells exhibit a low voltage plateau on discharge when the cells have been stored for an extended period, cycled extensively, or been subjected to uncontrolled handling (i.e., stored partially charged, stored at temperatures  $> 10^{\circ}\text{C}$ , subjected to overcharge at temperatures  $> 10^{\circ}\text{C}$ , or at rates higher than  $\text{C}/10$ ). The cells that exhibited second plateaus capacity below 1 V included three ISS cells, two HST, and two 120 Ah cells with longer wet life. This capacity accounted for up to 9 % of the total capacity measured at a  $\text{C}/2$  rate of discharge. Cells 224 and 306, the oldest of the cells from the ISS builds showed second plateaus that were not present in the ISS cells with shorter wet life as shown in Figure 1.



*Figure 1. 10°C Discharge Profiles for ISS 81 Ah Cells*

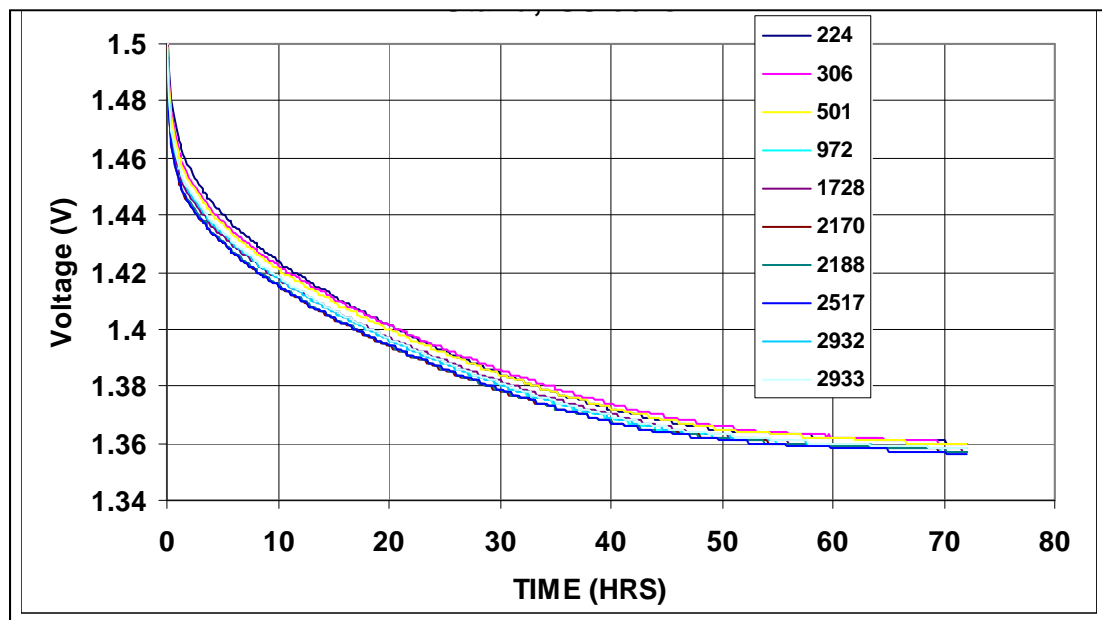
## 2.3. Resistor Drain Capacity

The capacity remaining after the power discharge to 0.1 V was measured by discharging through a resistor to determine the presence of low rate active materials in the positive plate. The values are shown in Table 1. The cells with long wet life tended to have more resistive capacity indicating the presence of positive active material that is capable of discharging at very low rates.

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## 2.4. Charge Retention

The cells in this study showed charge retention values ranging from 82.2% to 90.3% (see Figure 2). The general value for charge retention is 85% and the values yielded by most of cells were close to that thereby showing the absence of internal shorts in the cells. There was no clear correlation between wet life and charge retention values.



*Figure 2. Charge Retention 72-Hour Open Circuit Stand, ISS Cells*

## 2.5. Reversal Voltage

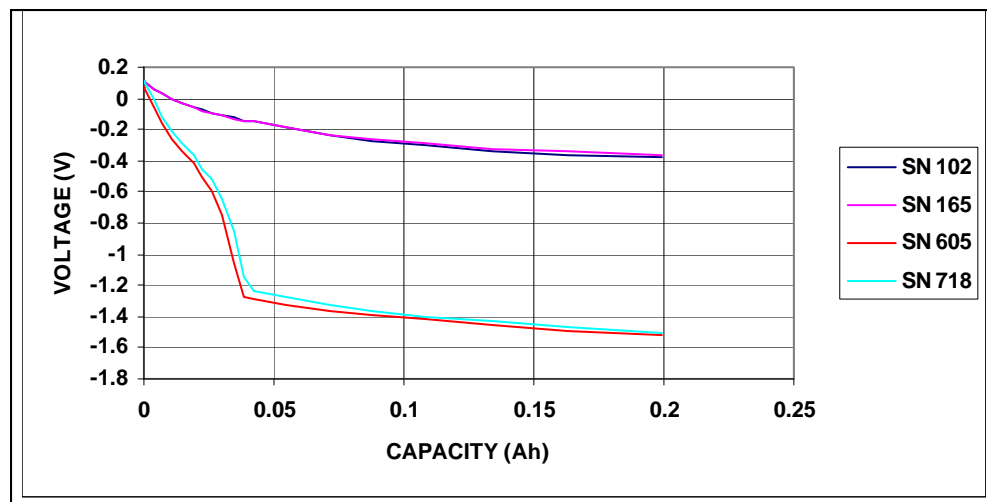
In general, the reversal voltage exhibited by cells with nickel precharge is  $< -0.35$  V. All the cells showed that value with the exception of several cells with longer wet life such as ISS 3-224 and 4-306 which showed  $-1.43$  V and  $-0.78$  V, HST 10-605 and 11-718 showed  $-1.51$  V, and the commercial 120 Ah cell 22-1997 which showed  $-1.23$  V. The larger negative values indicate the presence of a nickel precharge. It is not possible to quantitatively determine the amount of nickel precharge from the cell reversal voltage. A hydrogen precharge cell would have shown about  $-0.1$  V or closer to 0 V. Figure 3 shows the voltage behavior during reversal for the HST cells and 90-9 US Government cells in which the HST cells exhibited  $-1.5$  V for the reversal potential. Figure 4 shows the reversal voltages of the ISS cells.



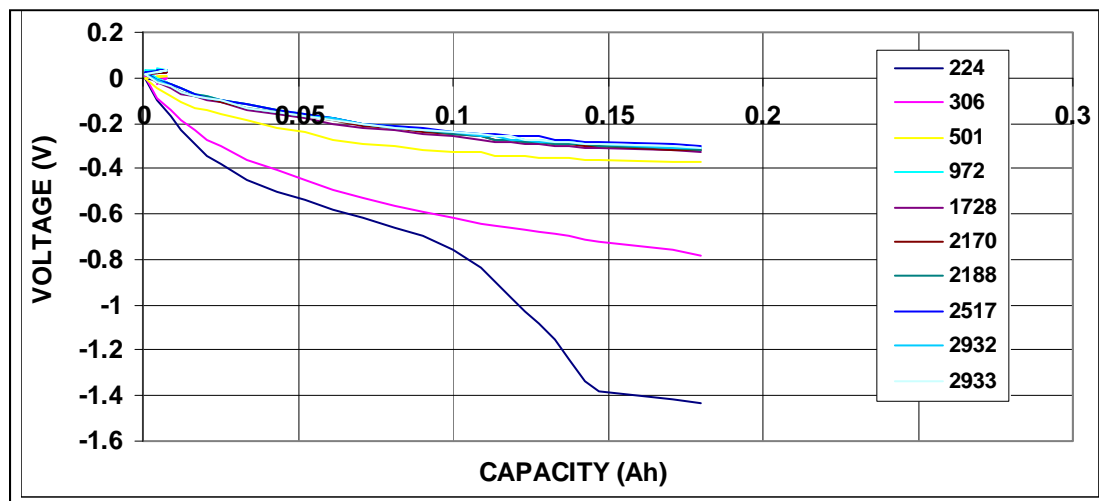
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*Figure 3. Cell Reversal for HST and US Government 90 Ah Cells*



*Figure 4. Cell Reversal for ISS Cells*

## 2.6. Voltage Rise

The voltage recovery of the cells from a completely discharged condition yielded a value  $< 0.159$  V that is in agreement with the value shown by nickel precharge cells. Thus, the behavior is unchanged with respect to wet life. Tables 1 and 2 give the voltage rise values for the cells.

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### 3.0. Gas Analysis


The gases in the cell at the conclusion of the electrochemical tests were determined. The presence of gas was not indicated in any of the cells. Results are presented in Table 2. Comparing reversal voltage and gas analysis, a state of positive precharge is indicated in all the cells under test.

**Table 2. Voltage and Gas Analysis**

Activation Date	S/N	VOLTAGE RISE*		Gas on opening
		after 1 hr	after 24 hr	
Jan-1995	122	0.015	0.069	No gas
Oct-1994	224	0.029	0.077	No gas
Dec-1998	1728	0.022	0.075	no gas
Oct-2001	2188	0.027	0.083	no gas
Jun-2004	2933	0.025	0.089	no gas
Mar-1997	102	0.022	0.064	no gas
Aug-2000	605	0.022	0.031	no gas
May-1997	1052	0.017	0.122	no gas
Aug-1997	1238	0.020	0.116	no gas
Feb-2004	2749	0.022	0.159	no gas
Nov-1997	5	0.017	0.033	no gas
* after resistor drain to 2 mV				

### 4.0. Cell Disassembly

The cells were opened in a discharged state and anomalies were noted upon disassembly. In all cells, the components were in the proper sequence and the separator coverage was adequate. The canisters weld rings and end plates did not show any evidence of structural damage, were positioned properly, and contained drops of electrolyte. The anodes, cathodes and separators were easily detachable. Table 3 presents a summary of the visual observation of the condition of the components.

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**Table 3. DPA Findings of All Cells**

ACTIVATION DATE	S/N	POSITIVE PLATES								NEGATIVE PLATES						SEPARATORS				SCREENS			
		small blisters	large blisters	erupted blisters	rough surfaces	scratched surfaces	weak pliable plates	bent plate	holes in plate surface	wetted	pinholes	burnmarks	compression marks	dirty tabs	loose Pt	dirt on positive side	Pt on negative side	green staining	tears from blisters	wetted	burnmarks	melting at tab	dirty
Oct-94	ISS 81 Ah S/N 224																						
Jan-95	EOS AM S/N 2-122																						
Mar-97	EPT 90-9 S/N 3-102																						
May-97	EPT 120Ah S/N 1052																						
Aug-97	EPT 120Ah S/N 1238																						
Nov-97	EOS PM S/N 1-5																						
Dec-98	ISS 81 Ah S/N 1728																						
Aug-00	HST 90-3 S/N 10-605																						
Oct-01	ISS 81 Ah S/N 2188																						
Jun-04	ISS 81 Ah S/N 2933																						

FREQUENCY KEY

not present or negligible


slight, found in less than 30% of modules

moderate, between 30 and 70%

extensive, greater than 70%

## 5.0. Electrolyte Analysis

The electrolyte was washed from all components of the disassembled stacks. The components were weighed before and after washing. Table 4 lists the weight of the electrolyte determined for each component. Results are listed as the average weight of electrolyte in each component as well as the weight of electrolyte per weight of component. The negative and positive plates in the subject cells contained similar amounts of electrolyte, except for the 120 Ah cell that contained greater electrolyte in the Positive plate, and consequently, less electrolyte in the

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separator. The amount of electrolyte in the separators tends to have the greatest variation over time, with greater amounts found in aged cells. The pre-activation storage mode may also influence electrolyte absorption during activation as components are stored under pressure (nitrogen).

The electrolyte was titrated to two separate endpoints to calculate the potassium hydroxide and potassium carbonate concentrations. Table 5 lists the electrolyte concentrations. KOH concentrations have remained similar, ranging from 28.4 to 30.7-weight percent and carbonate concentrations of 2.8 to 3.4-weight percent. The volume of electrolyte per Ah of theoretical capacity in the positive electrode has varied greatly, and been dependant on positive plate loading.

**Table 4. Electrolyte Distribution**

Activation		Cell Size	Pos.Plates	Neg Plates	Zircar	Screen
DATE	S/N	(Ah)	(g/g plate)	(g/g plate)	(g/g sep)	(g/g scrn)
Oct-94	224	81	0.14	0.04	1.28	0.08
Jan-95	2-122	50	0.14	0.05	1.42	0.12
Mar-97	3-102	90	0.14	0.04	1.38	0.07
May-97	1052	120	0.18	0.04	1.08	0.14
Nov-97	1-5	160	0.15	0.06	1.74	0.31
Dec-98	1728	81	0.14	0.03	1.35	0.20
Aug-00	10-605	90	0.15	0.05	1.31	0.05
Oct-01	2188	81	0.15	0.03	1.29	0.28
Jun-04	2933	81	0.13	0.03	1.24	0.15

The cc/Ah data calculation is in progress and shall be completed in due course.

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**Table 5. Electrolyte Concentrations**

Activation DATE	S/N	Cell Size (Ah)	KOH Conc. (%)	K <sub>2</sub> CO <sub>3</sub> Conc. (%)	cc/Ah
Oct-94	224	81	28.5	5.1	3.03
Jan-95	2-122	50	29.7	3.3	3.39
Mar-97	3-102	90	29.6	2.8	2.38
May-97	1052	120	27.1	4.7	2.82
Nov-97	1-5	160	28.4	3.4	3.73
Dec-98	1728	81	28.1	3.9	3.21
Aug-00	10-605	90	30.7	2.9	2.92
Oct-01	2188	81	28.0	4.0	3.18
Jun-04	2933	81	28.8	4.0	2.99

## 6.0. Separators

The Zircar separators were evaluated for their absorbency, resistivity and physical appearance. Table 6 displays these results. Results show the subject Zircar separators to be slightly lighter and thinner than the virgin sample. Weights and thickness from the Lot 10 cells are very similar, while the Lot 11 separator samples have been slightly thinner. The electrolyte absorbency of the separators from the entire group of cells was higher than that shown by a virgin sample. The cells with later activation dates tended to have lower absorbency.




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**Table 6. Separator Absorbency**

Act. Date	S/N	Cell Size (Ah)	Absorbency (g KOH/g sep)
1992	virgin	3.5"	2.0
Oct-94	224	81	2.8
Jan-95	2-122	50	2.9
Mar-97	3-102	90	2.7
May-97	1052	120	3.1
Nov-97	1-5	160	2.6
Dec-98	1728	81	2.5
Aug-00	10-605	90	2.5
Oct-01	2188	81	2.5
Jun-04	2933	81	3

## 7.0. Positive Plates

The positive plate analysis consists of removing the active and sinter material from the substrate and from each other. Table 7 presents the results from the chemical analysis. Generally, the virgin plates tend to weigh less, be thinner yet have higher porosity, and have higher loading than their cell counterparts. This suggests plate swelling and possible sinter corrosion even in these cells with little cycling. The baseline values that were used for comparison are: Ni active material of 35.03%; Ni sinter of 49.68%; cobalt of 5.75% of the active material; plaque porosity of 78% and total active material loading of 1.68 g/cc void. The results reported are incomplete since the analysis is in progress. The cells were also analyzed for potassium in the positive plate, which made up approximately 1.5% of the plate mass.

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**Table 7. Positive Plate Analysis Comparison**

Activation Date	Identification	Cell Ave. Weight (g)	Cell Ave. Thickness (mm)	Ni(OH) <sub>2</sub> (%g)	Co(OH) <sub>2</sub> (%g)	Co(OH) <sub>2</sub> % of active	Sinter (%g)	Substrate (%g)	POROSITY		LOADING		UTILIZATION	
									Sinter (%)	Plaque (%)	Ni (g/cc)	Total (g/cc)	Plate (%)	Cell (%)
1995	Virgin EOS AM Lot 2	13.05	0.767	33.19 4.33	2.02 0.26	5.66	48.64 6.34	13.15 1.71	80.4	75.8	1.48	1.71	121.6	NA
1997	Virgin HST Lot 11	15.28	0.925	36.68 5.53	2.39 0.36	6.11	46.46 7.00	11.34 1.71	82.3	78.5	1.51	1.74	106.3	NA
Oct-94	S/N 224 ISS 81 Ah		0.811	34.49 4.68	1.93 0.26	5.26	45.43 6.17	12.63 1.71	82.2	78.3	1.46	1.78	131.6	120.6
Jan-95	S/N 2-122 EOS AM	13.58	0.805	34.05 4.65	2.58 0.35	7.00	56.49 7.72	12.55 1.71	77.6	73.9	1.55	1.67	148.1	132.3
Mar-97	S/N 3-102 RNH-90-9	15.65	0.947	39.69 6.26	2.43 0.38	5.72	50.45 7.95	10.87 1.71	80.5	77.2	1.70	1.80	113.9	119.0
Dec-98	S/N 1728 ISS 81 Ah	13.59	0.797	33.95 4.61	2.07 0.28	5.73	47.19 6.41	12.61 1.71	81.2	77.3	1.49	1.76	145.5	125.1
Aug-00	S/N 10-605 RNH-90-3	15.49	0.943	34.76 5.31	2.46 0.37	6.51	51.66 7.88	11.23 1.71	80.6	77.3	1.44	1.54	128.5	127.0
Oct-01	S/N 2188 ISS 81 Ah	13.44	0.809	33.89 4.56	2.20 0.30	6.17	46.24 6.22	12.75 1.71	82.0	78.1	1.43	1.73	153.4	129.9
Jun-04	S/N 2933 ISS 81 Ah	13.47	0.787	34.18 4.60	2.34 0.32	6.50	46.25 6.23	12.73 1.71	81.5	77.5	1.50	1.80	151.1	131.0
Nov-97	S/N 1-5 EOS PM	23.28	0.826	30.68 7.15	2.24 0.33	4.41	54.66 12.74	14.33 3.34	78.0	73.7	1.41	1.43	171.7	152.0

## 8.0. Precharge Analysis

The capacity balance between the anode and cathode that is described as hydrogen precharge or nickel precharge was analyzed by several methods. For example, the absence of residual hydrogen in the cells at opening points to the presence of a nickel precharge. Only one cell from this study has had a positive pressure on opening. The positive plates were also discharged immediately after stack disassembly in flooded KOH. This test presented negligible residual capacity in cells to date. This capacity is considered to be the electrochemically active precharge. This value was lowest in the 90 Ah cells. Sample positive plates were also chemically analyzed with ferrous ammonium sulfate to determine the total charged nickel remaining in the plate. This value includes both the electrical and chemical portions of precharge.

Table 8 presents the precharge values to date. The cells retained their original design of nickel precharge, but the 90 Ah cells appear to have a loss in precharge when compared to other cells.

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**Table 8. Positive Precharge**

Activation	CELL ID	CELL CAPACITY		PRECHARGE CAPACITY		
		Rated Ah	Actual 20 °C Ah to 1.0 V	Electrical Ah	Chemical Ah	Total Ah
Oct-94	224	81	90.6	0.1	8.4	8.4
Jan-95	2-122	50	58.9	1.1	9.6	10.7
Mar-97	3-102	90	91.5	0.5	8.3	8.8
May-97	1052	120	130	progressing progressing		14.6
Nov-97	1-5	160	171.4	1.1	22.0	23.1
Dec-98	1728	81	89.7	1.9	14.6	16.6
Aug-00	10-605	90	82.4	0.2	9.7	9.9
Oct-01	2188	81	90.8	1.7	10.9	12.7
Jun-04	2933	81	94.4	1.2	15.1	16.3

## 9.0. Conclusions

*The study leads to the following conclusions:*

1. Cell capacity, charge retention, and voltage rise are not influenced by the wet life of cells.
2. Second voltage plateau occurs in cells with longer wet life.
3. There is no obvious correlation between wet life and the number and/or severity of blisters on the positive plates.
4. Coefficient of positive material utilization is unchanged.
5. All the cells studied indicated nickel precharge and the oldest cells showed a nickel precharge of 8.4 Ah.

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## Appendix B. Analysis of Stored Nickel-Hydrogen Battery Cells

Work performed under Contract Number NNL07AC79T

### Analysis of Stored Nickel-Hydrogen Battery Cells

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*The Aerospace Corporation*

#### Abstract

#### I. Introduction


The stability of nickel hydrogen cells during long-term storage is dependent on the presence of active nickel precharge in the cell during storage, which maintains an oxidizing electrochemical environment at the nickel electrode. An oxidizing environment makes the nickel and cobalt oxides in the electrode stable, while a reducing environment (resulting from hydrogen gas precharge) can react with these oxides to degrade their performance. Here we report the analysis of the type and amount of precharge in a number of nickel hydrogen cells that have been stored for long periods of time. The type precharge is evaluated by electrical measurements on each cell and analysis of the gas composition within the discharged cell, and the amount of active and inactive precharge is measured by analysis of nickel electrodes that were removed from cells.

A summary of the cells that were provided for analysis is given in Table 1.

**Table 1. Cells Used in Analyses**

Cell S/N	Capacity	Activation Date	Cell Diameter
165	90 Ah	1997	3.5"
718	90 Ah	2000	3.5"
104	50 Ah	??	3.5"
262	50 Ah	1996	3.5"
1997	120 Ah	1999	4.5"
1038	120 Ah	1997	4.5"
2749	120 Ah	2004	4.5"
15	160 Ah	1997	4.5"
306	81 Ah	1995	3.5"
2170	81 Ah	2000	3.5"
2932	81 Ah	2004	3.5"

While the detailed history of these cells is not known, it is known that the 50 Ah cell S/N 104 was the only one that had undergone extensive cycling. The other cells had only been exposed to long-term discharged cold-storage, that in some cases may have included periodic limited cycling for capacity verification.

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For the two 90 Ah cells, S/N 718 had been in continuous cold-storage since activation before being removed for capacity evaluation just prior to delivery to us for this work. In contrast, 90 Ah cell S/N 165 had been removed from cold storage about every 2 years for and cycled several times for capacity verification.

## II. Electrical Cycling of Cells

The cells were all exposed to a common electrical cycling sequence before analysis of the precharge within the cells. The purpose of this electrical cycling was to evaluate the post-storage performance of the cells, and to obtain voltage signatures that could potentially indicate the type of precharge in the cells. This sequence involved the following steps:

1. Standard Capacity Cycle at 10°C.  
Purpose: To measure the standard capacity of the cell. The cell should meet its rated capacity.  
Charge Regimen: C/10 rate for 16 hours  
Discharge Regimen: C/2 rate to 1V followed by C/10 to 0.5V, and then resistor drain (0.25 ohms) to 0.005V (16 hrs maximum)
2. Voltage rise test at 10°C:  
Determine the voltage rise profile under open circuit conditions for a 6-hr duration.
3. Charge Retention at 10°C.  
Purpose: To check for evidence of internal shorting.  
Charge Regimen: C/10 rate for 16 hours  
After full charge, the cell is open circuited for 72 hours and then discharged at C/2 rate to 1V followed by C/10 to 0.5V, and then resistor drain (0.25 ohms) to 0.005V (16 hrs maximum).
4. Standard Capacity Cycle at 20°C.  
Purpose: To measure the standard capacity of the cell.  
Charge Regimen: C/10 rate for 16 hours  
Discharge Regimen: C/2 rate to 1V followed by C/10 to 0.5V, and then resistor drain (0.25 ohms) to 0.005V (16 hrs maximum)
5. Cell reversal test at 20°C  
Purpose: To determine the potential at which the cell reverses.  
Discharge is continued in the following sequence:  
Resistor drain 0.25 ohms to 0.002V (16 hrs maximum).  
Discharge at C/40 for 5 minutes (reversal step).
6. Oxygen reduction step charge at 10°C  
Purpose: To determine the time required to recombine any oxygen generated during reversal.  
Charge: C/20 until the cell reaches 0.7V.  
Open circuit stand: Open circuit voltage will be monitored for at least 6 hr.





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### 1. Results from Standard Capacity Cycle at 10°C

The results for the recharge voltage signatures, the discharge voltage signatures, and the open-circuit stand voltage following complete discharge and let-down from the 10°C capacity test are indicated in Figure 1 through Figure 3.

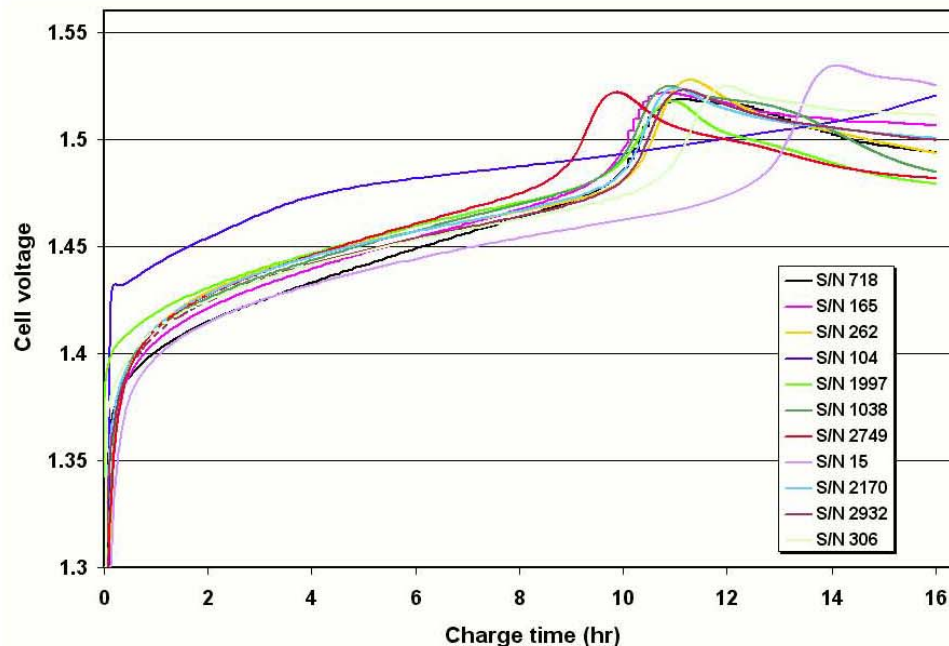


Figure 1. Cell voltages during C/10 recharge at 10°C.

The recharge voltages in Figure 1 are typical for nickel hydrogen cells that have some nickel precharge, with the exception of S/N 104. The higher charge voltage and the rapid rise and peaking at the initiation of recharge are all indicative of a fully depleted nickel electrode, suggesting that there is no active nickel precharge in this cell. Additionally S/N 1997 also shows a rapid voltage rise at the start of recharge, suggesting that it has very little active nickel precharge. The recharge voltage of cell S/N 15 differs from the other cells because this cell was only recharged at the C/13.33 rate rather than the C/10 rate. Thus it displayed a lower voltage and took longer to become fully recharged.

The discharge voltages at a C/2 rate (cell S/N 15 was only C/2.667) are indicated in Figure 2, and show that all the cells delivered their nameplate capacity, since they discharged for more than 2 hr (more than 2.667 hr for S/N 15). Following, a complete discharge and a resistive letdown to 0.005V, the open-circuit voltage recovery of the cells for 6 hr is shown in Figure 3. All the cells show a rising voltage, except for S/N 104, which is slowly falling toward zero volts, again suggesting hydrogen precharge for this cell. The other cells display a very wide range of voltage recovery rates, ranging from recoveries between 0.04 and 0.28V.



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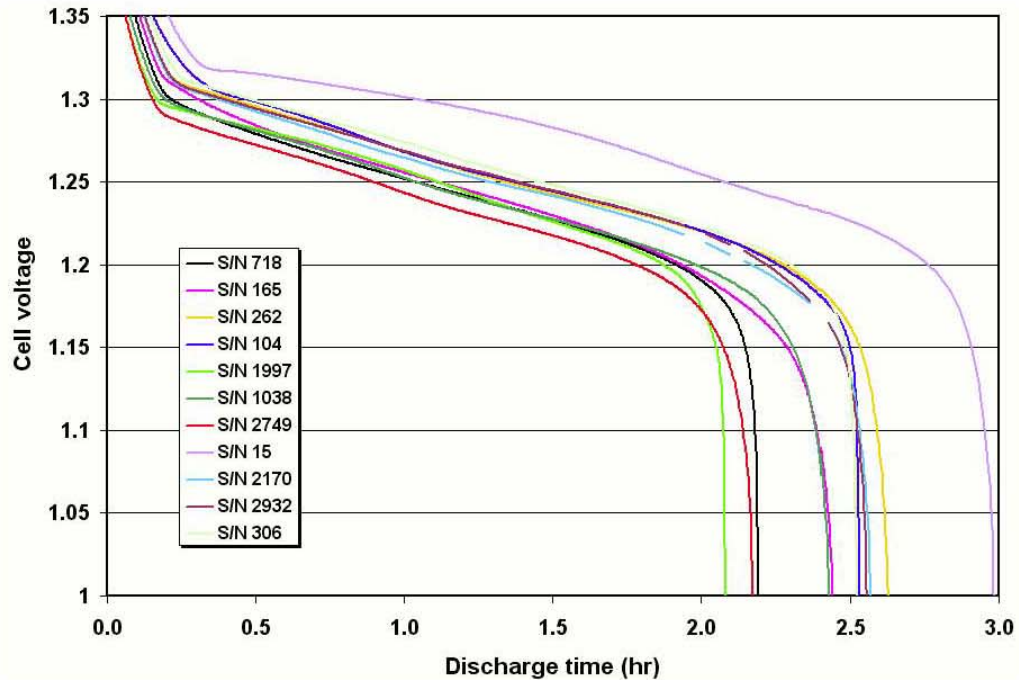


Figure 2. Cell voltages during C/2 discharge at 10°C.

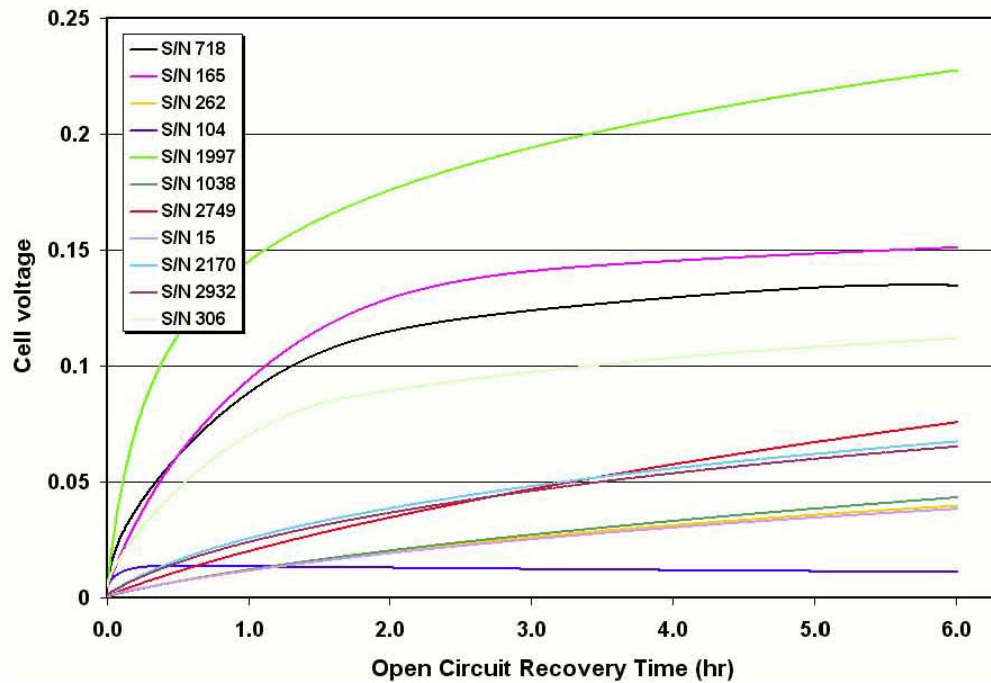
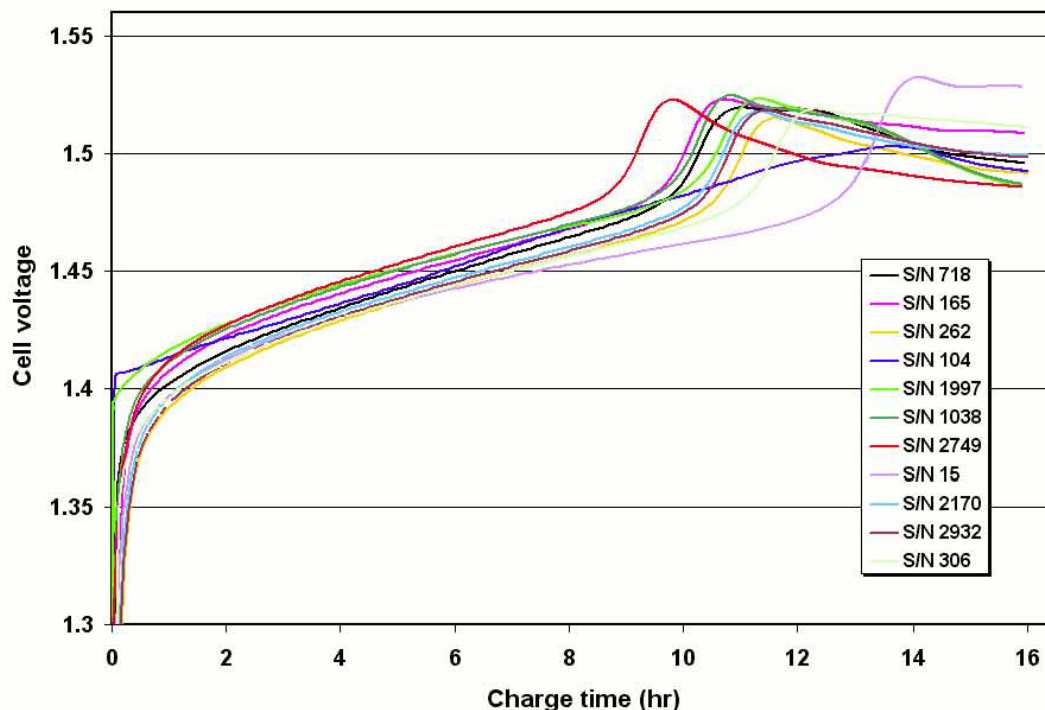


Figure 3. Cell voltages during 6-hr open-circuit stand at 10°C, following resistive letdown to 0.005V.



## 2. Results from Charge Retention Cycle at 10°C

The results for the recharge voltage signatures, the discharge voltage signatures, and the 72-hr open-circuit stand voltage between charge and discharge from the 10°C charge retention test are indicated in Figure 4 through Figure 6. Again the rapid rise in recharge voltage in Figure 4 at the beginning of recharge for S/N 104 suggests there is no active nickel precharge in this cell, and that cell S/N 1997 may have marginal active nickel precharge. The low peak charge voltage for S/N 104 also suggests that this cell may have reduced charge efficiency.



**Figure 4. Cell voltages during C/10 recharge at 10°C in the charge retention cycle.**

The 72-hr open-circuit voltage profiles shown in Figure 5 indicate that all the cells are well matched and in a tight distribution of open circuit voltages after 72 hr of stand. A possible exception is S/N 104, which has a higher than normal voltage, which can result from hydrogen precharge-induced modifications to the composition of the nickel electrode. The tight distribution of voltages after 72-hr of stand in Figure 5 indicates that there are no unusual losses from short circuits in any of these cells.

The discharge voltage profiles, which are shown in Figure 6, all appear to be normal, with the reduced capacity being the result of stand losses during the 72-hr open circuit period. The discharge capacities, which are shown in Table 2, are generally typical of well-performing cells, with all cells giving more than 85% charge retention. The exception is cell S/N 104, which had charge retention of only 80.61%, which is likely to be the result of some degradation to the nickel electrodes from hydrogen precharge.





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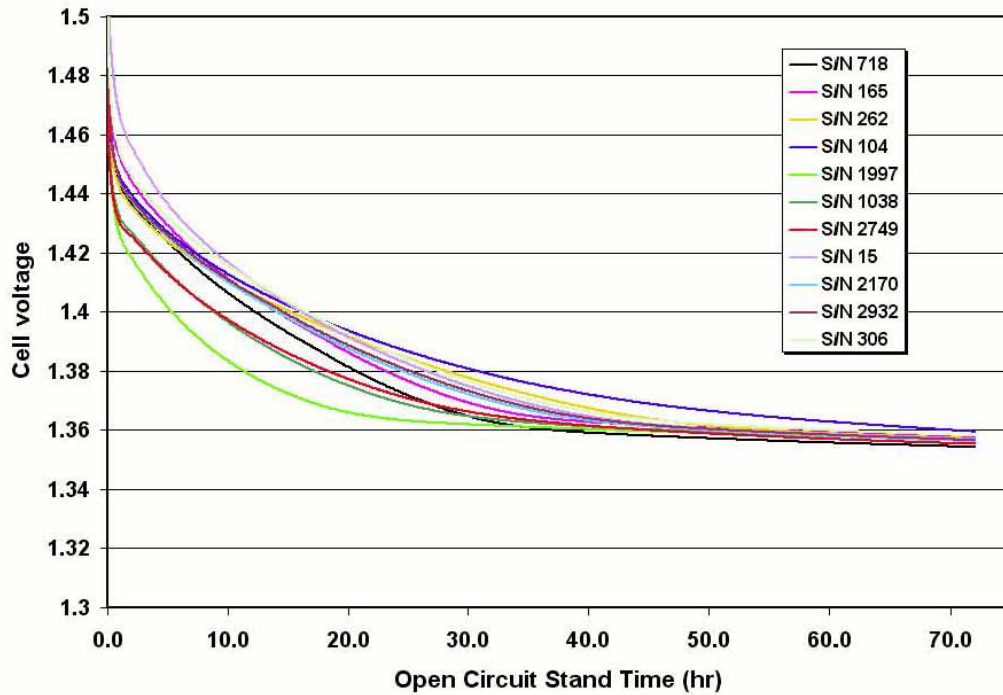


Figure 5. Cell voltages during 72-hr open circuit stand at 10°C during the charge retention cycle.

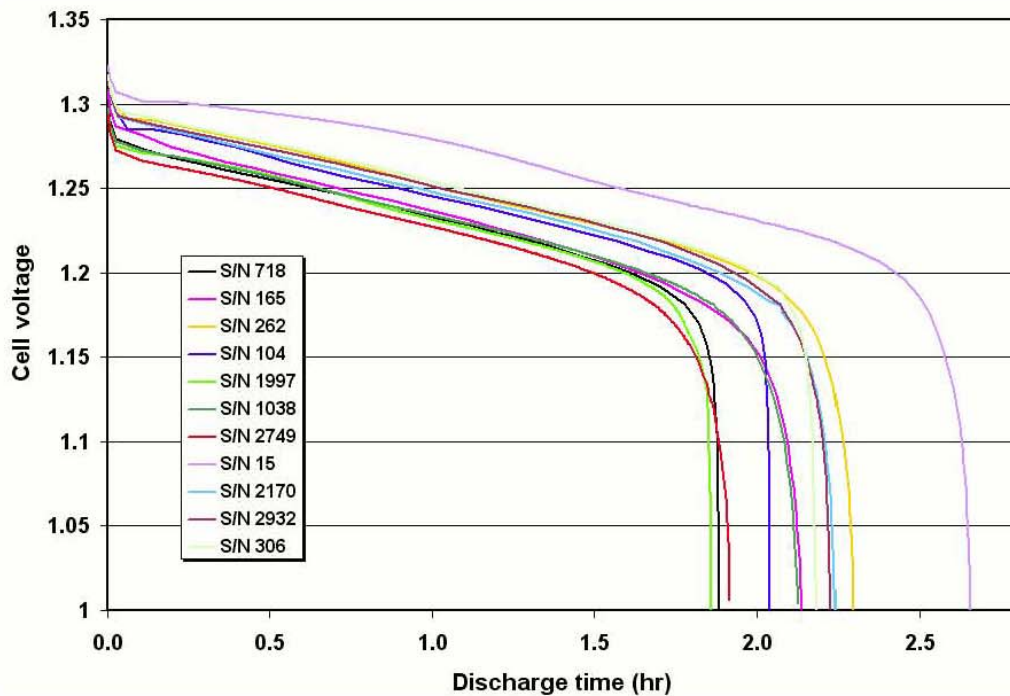


Figure 6. Cell voltages during C/2 discharge following stand in the charge retention cycle at 10°C.



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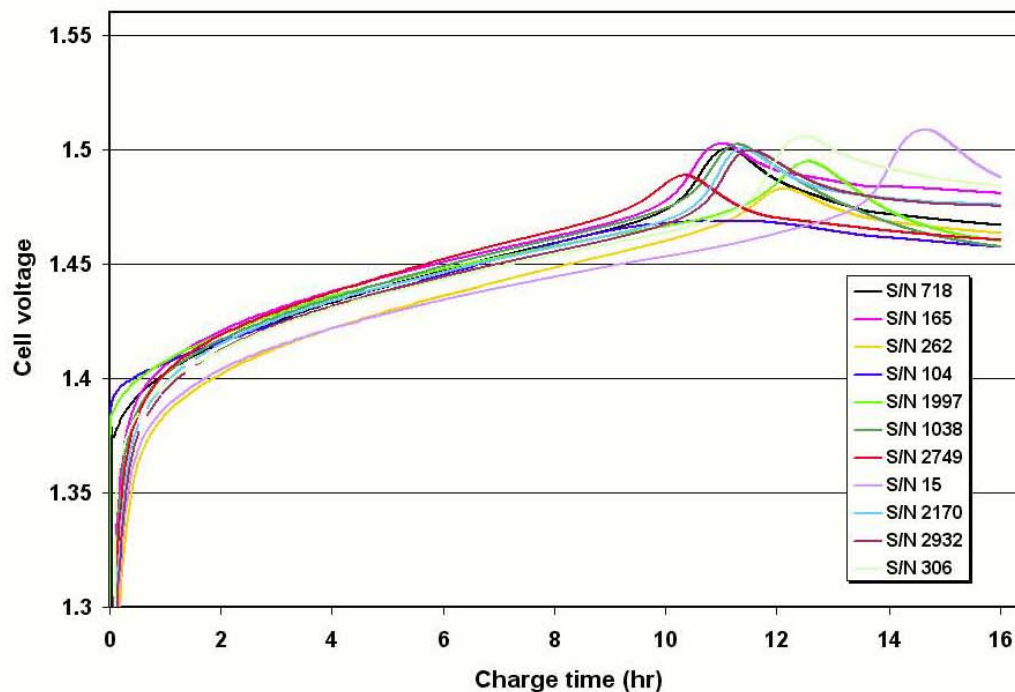
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**Table 2. Summary of 10°C capacities and reversal voltages measured for the cells.**

10 deg C Capacities	S/N	S/N	S/N	S/N	S/N	S/N	S/N	S/N	S/N	S/N	S/N
	165	718	104	262	1997	1038	2749	15	306	2170	2932
C/2 capacity	97.89	87.91	63.34	65.92	125.33	146.05	130.74	179.71	101.08	102.93	102.3
C/10 capacity	99.11	99.48	70.01	66.53	139.25	147.90	131.47	182.21	110.24	103.79	102.9
Chg ret capacity	85.75	75.56	51.06	57.49	111.70	127.97	115.33	159.81	87.49	89.98	89.20
Ch retention %	87.60	85.95	80.61	87.21	89.12	87.62	88.21	88.93	86.56	87.42	87.14
C/40 Reversal V	-0.383	-1.181	-0.043	-0.309	-1.206	-0.429	-0.341	-0.378	-0.505	-0.323	-0.317

### 3. Results from Standard Capacity Cycle at 20°C

The results for the recharge voltage signatures and the discharge voltage signatures from the 20°C capacity cycle are indicated in Figure 7 through Figure 9. The charge voltage signatures in Figure 7 are similar to those at 10°C except that the voltages are somewhat lower at the higher temperature. Similarly the C/2 discharge behavior shown in Figure 8 is fairly typical in terms of the discharge voltage plateau levels seen. The residual capacity discharged at the C/10 rate, and shown in Figure 9, indicates that all the cells except S/N 718, 104, 1997, and 306 have very little residual capacity at the lower plateau discharge voltage level. This suggests that these four cells may have either very low or no active nickel precharge.



**Figure 7. Cell voltages during C/10 recharge at 20°C during the standard capacity cycle.**



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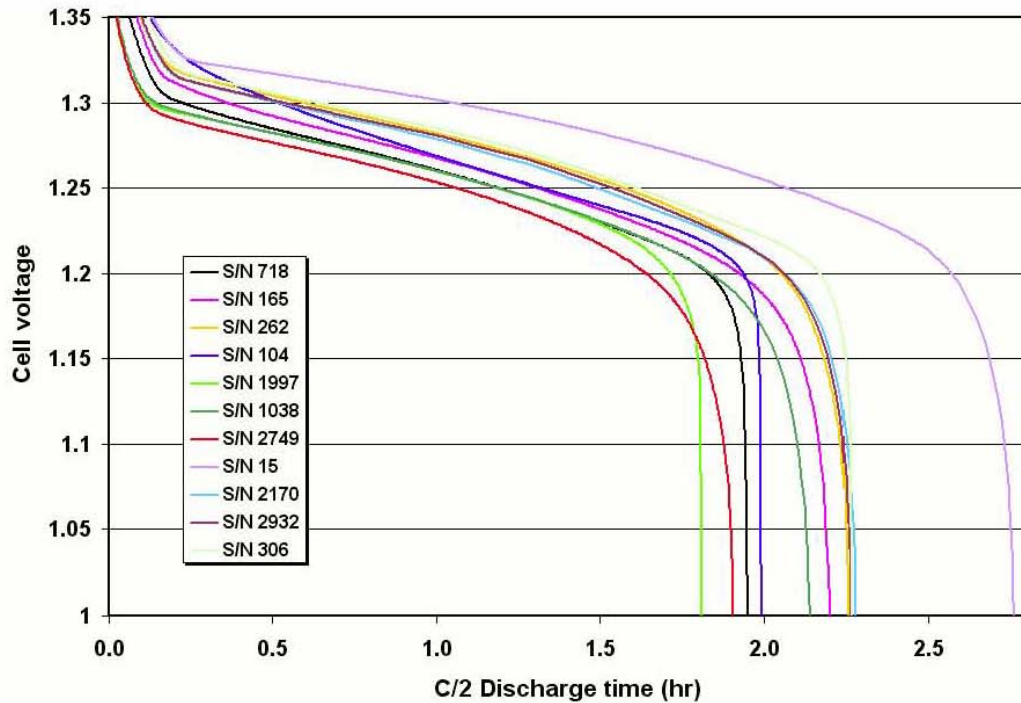


Figure 8. Cell voltages during C/2 discharge at 20°C during the standard capacity cycle.

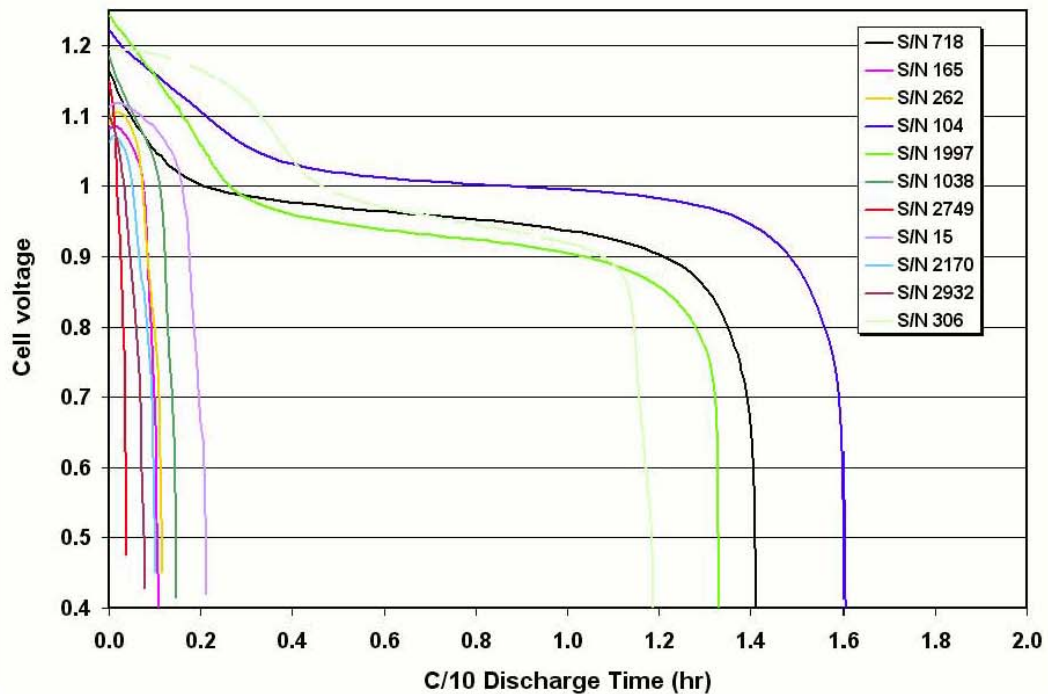


Figure 9. Cell voltages during C/10 discharge at 20°C during the standard capacity cycle.



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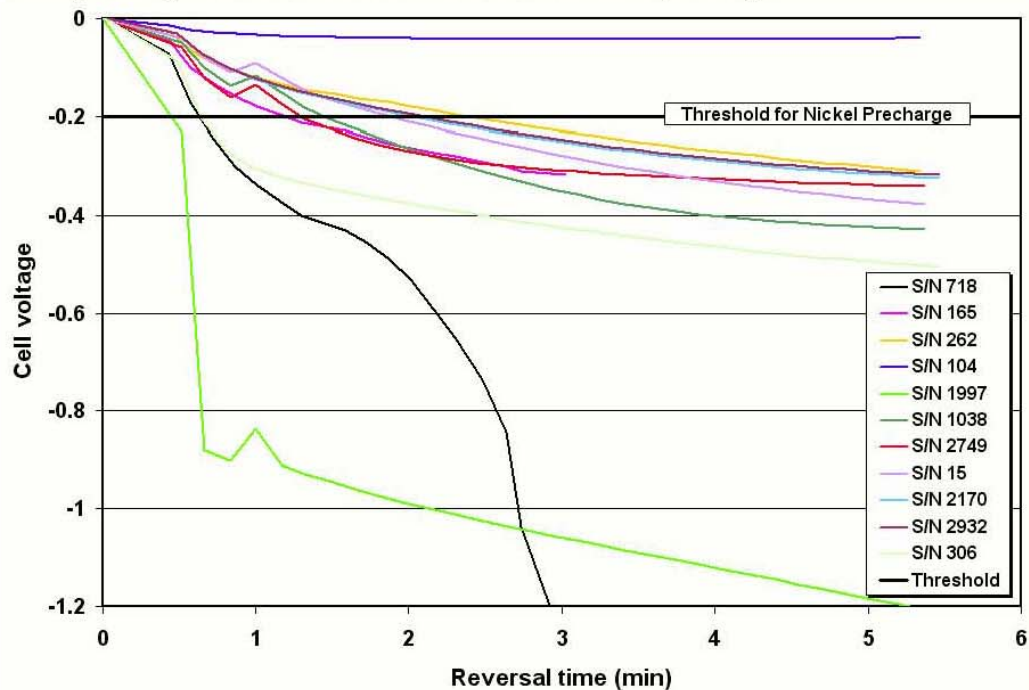
The capacities obtained from each cell in the 20°C capacity test are provided in Table 3. This table shows the significant level of residual (or second plateau) capacity seen for cells S/N 718, 104, 1997, and 306. In addition, the C/2 capacity for 50 Ah cell S/N 104 is nearly 7 Ah lower than that for the similar cell S/N 262, suggesting that cell S/N 104 has experienced a high-rate capacity fade of about 11.7%.

**Table 3. Summary of 20°C capacities measured for the cells.**

20 deg C Capacities	S/N 165	S/N 718	S/N 104	S/N 262	S/N 1997	S/N 1038	S/N 2749	S/N 15	S/N 306	S/N 2170	S/N 2932
C/2 capacity	88.20	78.18	49.96	56.61	107.54	127.42	113.32	164.90	90.80	91.26	90.69
C/10 capacity	89.32	89.61	58.01	57.21	123.54	129.23	113.82	167.49	100.30	92.08	91.31

### 4. Results from Reversal Cycle at 20°C

The results for the voltage signatures during the 5-min reversal after letdown to 0.002 V are shown in Figure 10, along with the -0.2V threshold that the voltage has to go below to indicate active nickel precharge. Only one cell, S/N 104 clearly has hydrogen precharge, as indicated by its voltage staying well above -0.2 volts during the 5-min reversal. Two other cells drop below -1.0 volt during the brief reversal period, which indicates that, while they do not have hydrogen precharge, they also have little active nickel precharge. All other cells have some active nickel precharge.



**Figure 10. Cell voltages during C/40 reversal at 20°C following letdown to 0.002V.**





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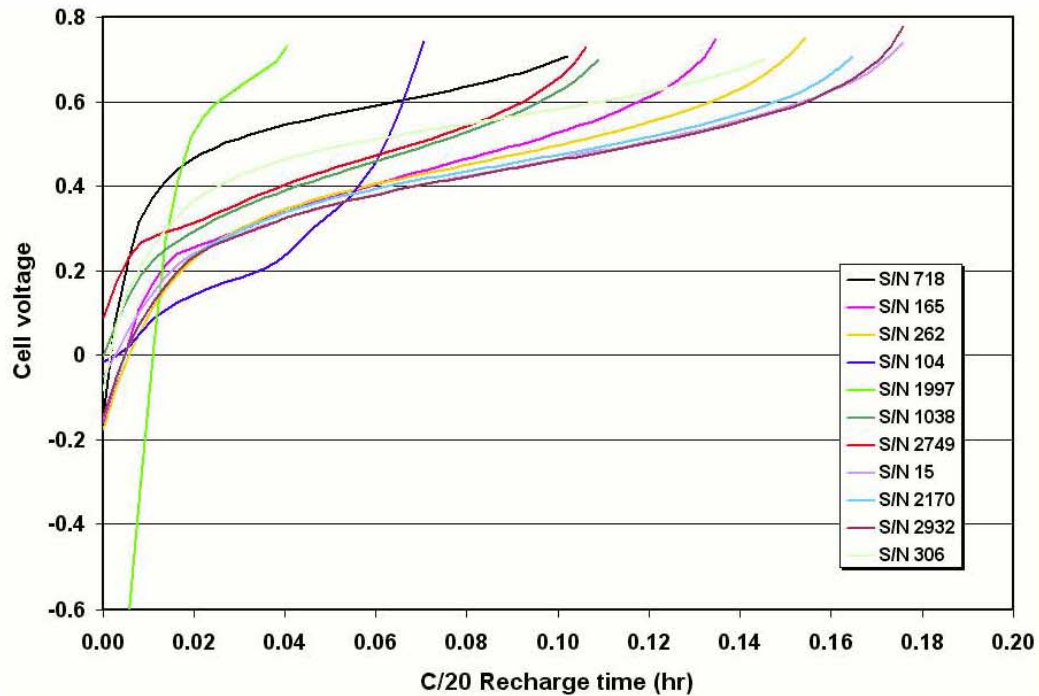


Figure 11. Cell voltages during C/20 recharge following reversal at 20°C.

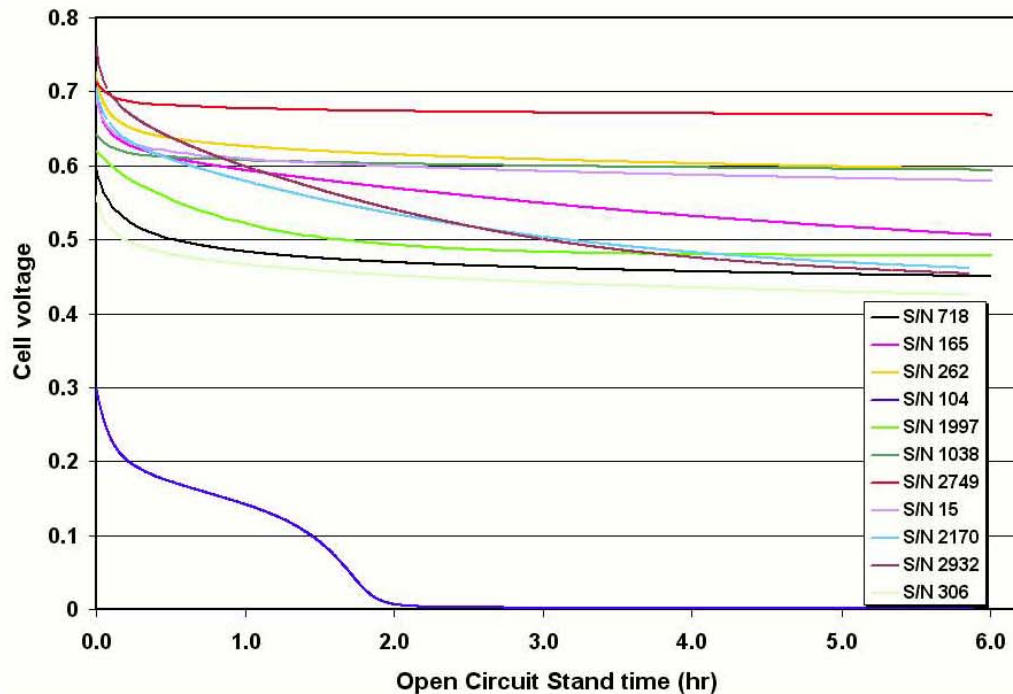



Figure 12. Cell voltages during 6-hr of open circuit stand at 20°C following recharge to 0.7V.

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Recharge to 0.7V following reversal will give a plateau at 0.4-0.5V as any oxygen gas in the cell that was generated by the reversal or by the precharge in the nickel electrodes, undergoes recombination. The recharge results are shown in Figure 11, which shows that all the cells except S/N 104 and S/N 1997 had a significant oxygen recombination plateau. This result, in combination with the reversal voltage signature, assures that there will be at least some active nickel precharge in the cell if it is put into storage following these tests.

The open circuit voltages of the cells for 6 hr following the recharge to 0.7 volts is shown in Figure 12. All the cells settle to voltages between 0.4 and 0.7 volts, except S/N 104, which drops to near zero volts within several hrs. The zero volt signature within a time as short as 2-hr is indicative of a substantial hydrogen precharge in cell S/N 104. Lower levels of hydrogen precharge can make cell voltages drop more slowly towards zero volts, and at some point it becomes difficult to differentiate an open circuit voltage that is slowly dropping because of nickel precharge from one that will eventually go to zero volts due to hydrogen precharge.


Table 4 summarizes the reversal and recovery voltages for all the cells tested.

**Table 4. Summary of recovery and reversal voltages seen in test cells.**

Cell S/N	Capacity	Activation Date	Recovery Voltages After 8 hr open-circuited		Reversal Voltage	Recovery volta Post reversal
			10 deg Cap test	Chg retention		
165	90 Ah	1997	0.15	0.1265	-0.383	0.488
718	90 Ah	2000	0.129	0.1246	-1.181	0.445
104	50 Ah	??	0.0105	1.27	-0.043	0.0016
262	50 Ah	1996	0.0466	0.0769	-0.309	0.589
1997	120 Ah	1999	0.242	0.17	-1.206	0.479
1038	120 Ah	1997	0.052	0.092	-0.429	0.591
2749	120 Ah	2004	0.091	0.074	-0.341	0.667
15	160 Ah	1997	0.045	0.07	-0.378	0.573
306	81 Ah	1995	0.075	0.48	-0.505	0.416
2170	81 Ah	2000	0.117	0.195	-0.323	0.449
2932	81 Ah	2004	0.077	0.191	-0.317	0.44

### III. Gas Analysis of Cells

A key method for determining the precharge of a nickel hydrogen cell involves measurement of the pressure and composition of the gas within the fully discharged cell. This procedure involves placement of the cell within an evacuated chamber that has an accurately calibrated internal volume, where the cell is punctured to allow its internal gas to escape. Measurement of the gas pressure within the chamber, along with calibration of the internal volume of the cell, allows calculation of the total pressure within the cell before it was punctured. A sample of the gas from the cell is collected in a stainless-steel gas-sampling bottle, and a residual gas analyzer is used to determine the composition of the gas mixture that existed in the cell.

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The key gases in this analysis are hydrogen and oxygen, since they are not seen to co-exist at significant levels in the nickel hydrogen cell environment. If oxygen gas is seen, the cell must have some active nickel precharge. If hydrogen gas is seen, the cell has a hydrogen precharge that is proportional to the absolute pressure of hydrogen gas in the cell. If the oxygen gas within the cell has been electrochemically recombined by a recharge to 0.7 volts (as was done in this study), only small amounts of oxygen will be expected, perhaps with small amounts of hydrogen gas. In this case the precharge will be nickel if the molar ratio of oxygen to hydrogen gas is greater than 1:2, or nickel precharge if it is less than 1:2.

The gas analyses from the nickel hydrogen cells that were analyzed are summarized in Table 5 and Table 6. This analysis provides the internal cell space for gas, the total gas pressure within the cell, and the composition of the gas.

**Table 5. Gas analysis results for 90 Ah and 50 Ah cells.**

Gas Analysis	RNH 90-9	RNH 90-3	RNH 50-104	RNH 50-262
	S/N	S/N	S/N	S/N
	165	718	104	262
Volume in cell (cc)	643.46	708.71	571.1	612.73
Pressure in cell (psia)	1.36	0.78	41.39	1.25
Hydrogen pressure (psia)	0.000272	0.0156	38.9066	0.01
Helium pressure (psia)	0.000136	0.000312	ND	0.000375
Methane pressure (psia)	0.000544	0.00312	0.037251	0.0025
Water vapor pressure (psia)	0.00544	0.4056	1.2417	0.2875
Nitrogen pressure (psia)	0.9928	0.3198	1.11753	0.925
Oxygen pressure (psia)	0.34	0.02808	ND	0.0125
Argon pressure (psia)	0.01496	0.00702	0.004139	0.003375
Carbon dioxide pressure (psia)	0.000408	0.00156	0.004139	0.000875

**Table 6. Gas analysis results for 120 Ah, 160 Ah, and 81 Ah cells**

Gas Analysis	RNH 120-1997	RNH 120-1038	RNH 120-2749	RNH 160-15	RNH 81-306	RNH 81-2170	RNH 81-2932
	S/N	S/N	S/N	S/N	S/N	S/N	S/N
	1997	1038	2749	15	306	2170	2932
Volume in cell (cc)	1552.04	1589.86	1680.34	2294.93	831.92	907.08	826.57
Pressure in cell (psia)	0.7027	0.6363	0.5951	1.0318	1.128	1.145	1.079
Hydrogen pressure (psia)	0	0.003182	0.005356	0.004127	0.00564	0.00458	0.000216
Helium pressure (psia)	0	6.36E-06	5.95E-05	0.000103	0.000113	0.00229	0
Methane pressure (psia)	0.000281	0.005727	0.007141	0.002064	0.001241	0.00229	0.003237
Water vapor pressure (psia)	0.007027	0.101808	0.172579	0.123816	0.19176	0.1374	0.004316
Nitrogen pressure (psia)	0.519998	0.515403	0.392766	0.866712	0.92496	0.97325	0.78767
Oxygen pressure (psia)	0.168648	0.005727	0.009522	0.006191	0.009024	0.00687	0.26975
Argon pressure (psia)	0.00773	0.003182	0.003571	0.019604	0.003384	0.008015	0.016185
Carbon dioxide pressure (psia)	0.000281	0.001273	0.00238	0.002064	0.001128	0.000573	0.000755





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The only cell that contained significant internal pressure was S/N 104, which contained 41.39 psia of gas, almost all of which was hydrogen gas. No oxygen was detected in this cell. This is the only cell of the ones analyzed that had hydrogen precharge, a result that is consistent with the electrical measurements. All the other cells had a level of oxygen gas that gave a oxygen to hydrogen ratio significantly greater than 1:2, meaning they all had at least some nickel precharge.

The other gases of interest in this analysis are methane, which comes from hydrogenated organic contaminants in the cell; nitrogen and argon, which come from atmospheric contamination during cell activation; helium, which comes from leak checks done on the cell when built; and carbon dioxide, which comes from oxidized organics or atmospheric contaminants and is expected to be in equilibrium with carbonates in the electrolyte. The sum of all these electrically inert gases should be below several psi, or they will block the flow of hydrogen into the gas screens during high rate discharge, and result in significantly reduced high-rate cell capacity. In all these cells the inert gas load was only about 1 psia or less.

### IV. Nickel Electrode Analysis


The electrical tests and gas analyses described in the previous sections can indicate whether the precharge in a nickel hydrogen cell is nickel or hydrogen. The gas measurements do indicate the amount of precharge if a cell has net hydrogen precharge. However, these measurements provide no quantitative measure of the amount of nickel precharge in cells that contain active nickel precharge. The amount of nickel precharge can be determined by reverse discharging a cell at low rate until the voltage falls to below -1.0 V. However, if this possibly extended reversal is not desirable, the amount of nickel precharge is best determined by removing the nickel electrodes from the cell and measuring the electrochemical and the chemical precharge within samples of nickel plates. Six of the cells in this study, as indicated in Table 7, were selected for measurement of the amount of nickel precharge by such analysis.

**Table 7. Results from electrochemical and chemical analysis of nickel electrodes from selected cells.**

Ni Plate Analysis	RNH 90-9	RNH 90-3	RNH 50-	RNH 120-	RNH 160-	RNH 81-
	S/N	S/N	S/N	S/N	S/N	S/N
	165	718	262	1038	15	306
Electrically active precharge (%)	2.61	0.04	3.13	1.94	1.75	1.60
Chemically active precharge (%)	12.18	12.69	12.64	13.53	12.07	12.05
Total precharge (% of rated cap)	14.79	12.73	15.77	15.46	13.83	13.66
Platinum oxide (wt % of active mat.)	0.73	0.25	0.32	0.44	0.52	0.33
Active loading (g/cc void)	1.59	1.76	1.57	1.21	1.53	1.73
Cobalt hydroxide (wt % of active mat.)	5.86	4.41	5.49	8.44	5.94	5.02
Thickness (mils)	36.81	38.96	32.62	40.22	32.52	31.52

The electrically active nickel precharge was measured by removing three nickel plates from each cell stack, immersing these plates in a 31% KOH electrolyte flooded cell



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that is equipped with a Hg/HgO reference electrode and a nickel sheet counter electrode. The plate was then discharged at a 1.0 ma/cm<sup>2</sup> rate until its voltage fell to -0.5 V vs. Hg/HgO, and then discharged at a 0.1 ma/cm<sup>2</sup> rate until its voltage fell again to -0.5 V vs. Hg/HgO. The electrically active nickel precharge is the sum of the capacity discharged at both these rates, and is reported in Table 7 as the average of that obtained from the three plate samples.


The electrically active nickel precharge from all these nickel electrodes ranged from about 1.5 to 3% of the rated cell capacity, with the exception of cell S/N 718, which had almost no active nickel precharge. This result is in agreement with the reversal voltages summarized in Table 4, which shows cell 718 dropping rapidly to below -1 V during C/40 reversal, while all the other cells exhibited a voltage plateau near -0.4 volts that corresponded to discharge of the active nickel precharge.

The chemical precharge in each electrode was measured following the electrical discharge by separating the grid structure, grinding the sinter and the active material into a fine powder, and magnetically isolating the active material from the sinter. The active material was then analyzed for chemical charge by reacting it with a known amount of ferrous ammonium sulfate, which is oxidized by the charged active material, and then back titrating the unreacted ferrous ions with a standard potassium permanganate solution.

The amount of chemical charge in the nickel electrodes is reported in Table 7 as the average of that obtained from the three plate samples. The total precharge built into typical nickel hydrogen cells when new is 12 to 15% of their rated capacity. This total is reported in Table 7 as the sum of the electrically active and the chemical precharge, and is seen to be in the range of 12.73 to 15.77% for all the cells analyzed. This result suggests that the gradual loss of active precharge during storage for these cells is accompanied by an equivalent increase in the inactive or chemical precharge. These results suggest that cell S/N 718 could have significantly lower active precharge because it was originally activated with several percent lower nickel precharge than the other cells.

The chemical analysis provides the active material loading in g/cc void in Table 7, along with the average thickness measured for the electrodes, the wt. % cobalt, and the wt. % platinum in the active material. The loading levels were calculated assuming 76% plaque porosity in the "as-produced" nickel electrodes. The loading level in many of the cells' nickel electrodes is lower than the 1.7 g/cc void at which they are loaded when new. However, this arises from the swelling seen over the normal 30 or 36-mil thickness that the new electrodes typically have, depending on the design. Interestingly, the cells with unusually high loading levels, S/N 718 and 306 were also the cells that seemed be lowest in nickel precharge, suggesting that corrosion of the sinter could play a role in the loss of active precharge. However, cell S/N 306 had also been stored longer than any of the other cells, thus giving more time for slow sinter corrosion processes to occur.

The cobalt level in these nickel electrodes was determined to range from 4.4 to 8.4% of the nickel in the active material, which is a typical range around the 5% level built into normal electrodes of these designs. The platinum in the nickel electrodes accumulates during storage as the result of oxidation at the catalyst electrode. The results in Table 7 show the Pt to range from 0.25 to 0.83% of the active material by weight. The platinum accumulation in the nickel electrode has not been found to correlate with

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performance problems, and can plate back onto the hydrogen electrode during cell cycling when the precharge becomes depleted. Thus it should be kept in mind that all these stored cells contain significant reservoirs of oxidized platinum in their nickel electrodes, and subsequent handling and operation of the cells should avoid conditions where these platinum oxides can be reduced to platinum metal on the nickel electrode.

## V. Conclusions

Eleven nickel hydrogen cells that had experienced varied storage durations and conditions were analyzed to evaluate the electrical and chemical signatures resulting from the precharge in the cells. Ten of the eleven cells were found to have some active nickel precharge, while the eleventh cell, S/N 104, was found to have 38 psia of hydrogen precharge. The electrical signatures from these cells were generally capable of differentiating between the nickel precharged condition and the extreme hydrogen precharged condition. The signatures from the reversal test were the most definitive in detecting the type of precharge in the cells. The open circuit voltage recovery signatures could also detect the high level of hydrogen precharge, but may not be capable of detecting low levels of hydrogen precharge.

The cells with some active nickel precharge had all appeared to have lost a significant portion of the nickel precharge that would be expected in new cells. The two 90 Ah cells were of significant interest because the oldest cell (S/N 165) had significant active nickel precharge (2.61%) while S/N 718, which was activated 3 years later had only 0.04% active nickel precharge. Of these two cells, the older cell was cycled to check capacity about every two years, while the newer cell saw only continuous cold storage. Several possible explanations exist for this difference. The first, which was supported by the chemical analysis of the nickel electrodes, is that cell S/N 718 received several percent less nickel precharge when it was manufactured, and thus ran out of active precharge earlier in its storage life. The second possibility is that periodically cycling a cell can help keep its precharge active, at the risk of inducing hydrogen precharge at the point in its storage life when the active nickel precharge is gone. This second possibility is somewhat counterintuitive, since periodic cycling of cells has typically been assumed to accelerate the depletion of active nickel precharge. A controlled test of how periodic cycling affects active nickel precharge is recommended, using cells of identical design and activation, to fully evaluate these possibilities.



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## Appendix C. Accelerated Cycle Test Report

Accelerated LEO studies were conducted on two, five-cell packs of cells with long wet lives. The packs were tested at the Naval Systems Warfare Center, Crane Division battery test facility. All cells had been stored discharged at  $0\pm5^{\circ}\text{C}$  and had minimal cycling beyond the Acceptance Test Procedure (ATP) cycles. Electrical characterization data were comparable to the Lockheed Martin/COMSAT Corporation and TAC results. The cell packs were subjected to accelerated testing at 60-percent depth of discharge (DOD) in a 90-minute LEO orbit that consisted of 30 minutes of discharge and 60 minutes of charge, at  $10^{\circ}\text{C}$  with voltage/temperature (VT) charge control.

The packs were designated 7604W and 7605W. A third pack, 7606W was added as a replacement when Pack 7604W was damaged during the life cycle test due to an equipment failure after ~1200 cycles.

Pack 7604W was comprised of five Eagle-Picher 90-9 cells from US Government programs, activated in March 1997. The cells were built at the Eagle-Picher, Joplin location using positive electrode plaque from the Eagle-Picher Colorado Springs plant that was impregnated at the Joplin by the C-Street (Joplin Plant) process. Life cycle testing on these cells started in August 2007. This pack failed at cycle 1198 due to a test system failure which left the test in the charge condition at the maximum charge rate of 65 amps. The pack was discontinued. The cells were returned to Eagle-Picher.

Pack 7605W was comprised of five, 81 Ah, Eagle-Picher cells manufactured for ISS, activated on May 27, 1997. The initial evaluation on these cells was completed on October 26, 2007, with life cycle testing starting in November 2007.

Pack 7606W comprised of five Eagle-Picher 90-9 cells from US Government programs. Four of the cells were activated in April of 1995 and the fifth cell was activated in March 1997. Life cycle testing on these cells was initiated in May of 2008.

As of November 2009, Pack 7605W, comprised of the ISS cells, had completed ~12,000 nominal cycles and had started to show signs of decay after 11,500 cycles. The US Government cell pack (7606W) had completed ~9,000 cycles. Pack 7606W experienced low end-of-discharge-voltages (EODVs) and cell divergence at 7,200 cycles. The DOD was reduced from 60 % to 15 % DOD, a level more representative of an HST profile.

Trend plots and full cycle plots for each of these packs follow.



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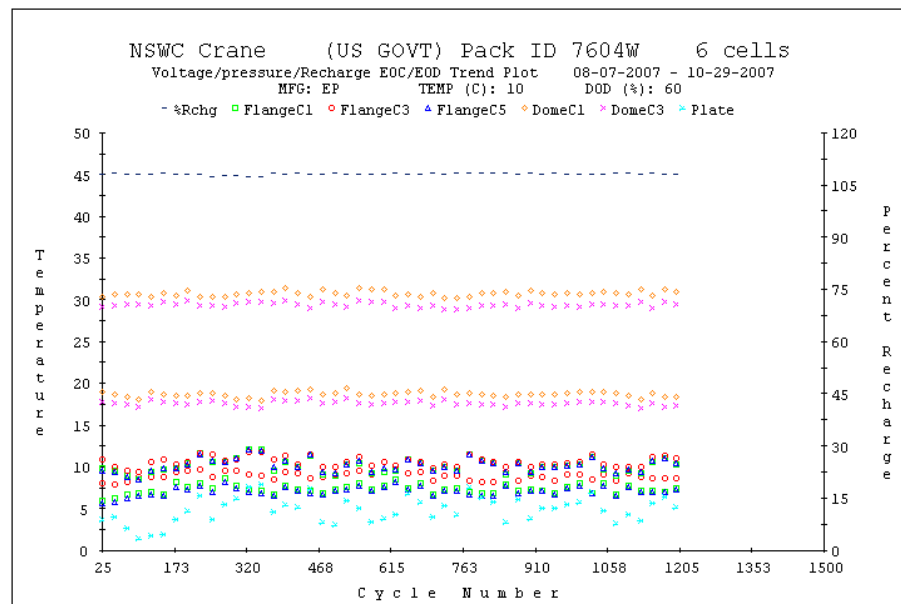
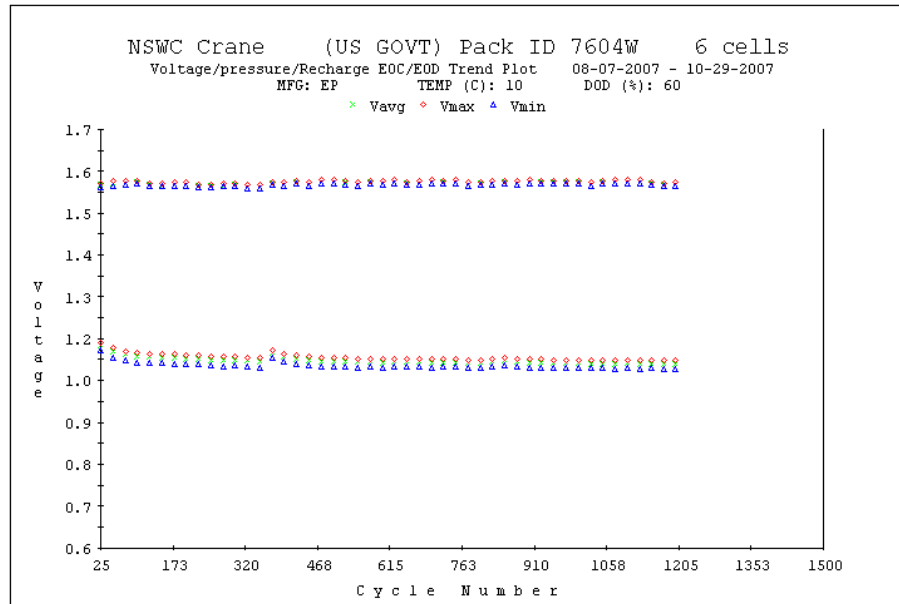
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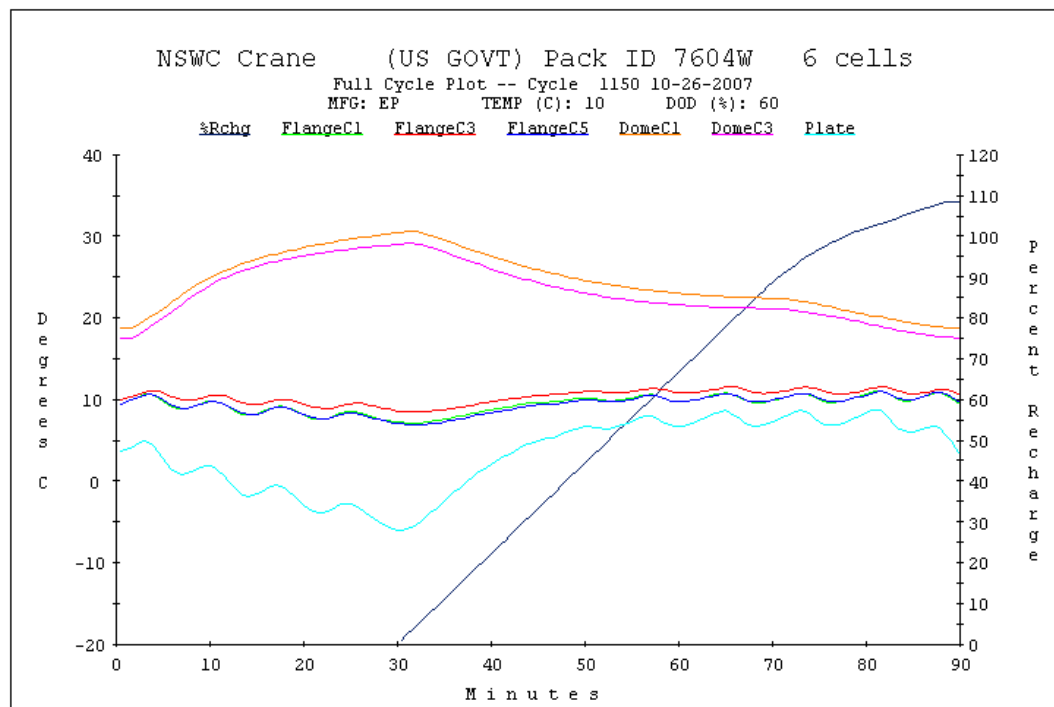
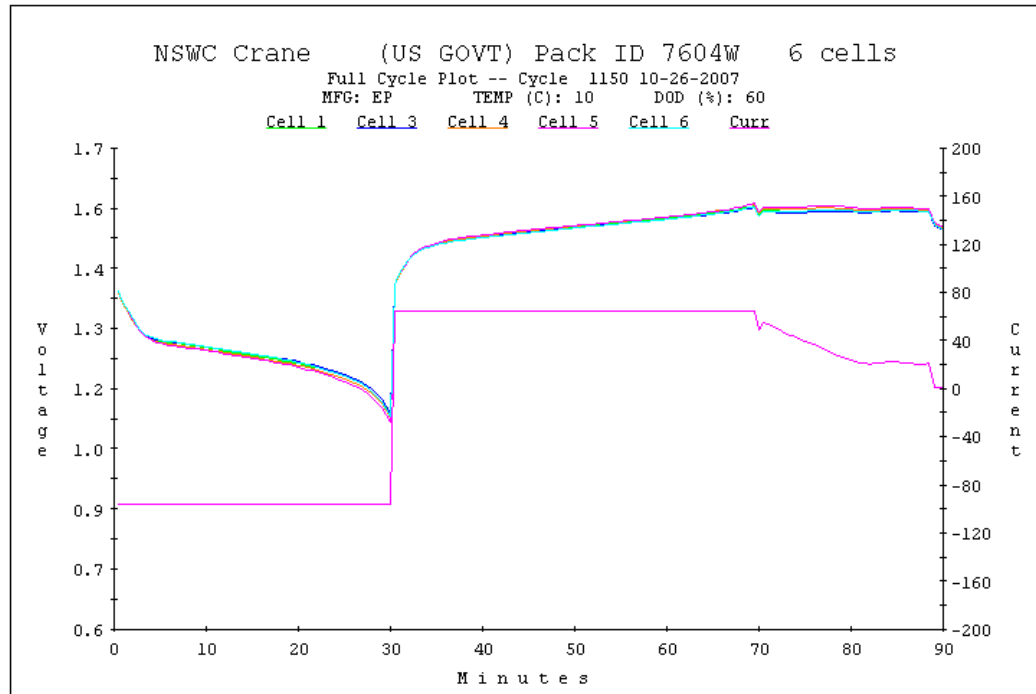
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Wet Life Study Update:

Pack 7605W:

Cell Description: 5 ISS 81 Ah cells manufactured by Eagle-Picher and activated May 27, 1997.

Loral/SS part #E005140-02.

Initial Evaluation: Completed 10/26/2007.

Life Cycle: Began 11/14/2007.

Test Conditions: LEO Stress test – 60% DOD, Orbit Period 90 minutes (30 minutes discharge, 60 minutes charge), @10°C. Charge control = VT.

Status: Completed 1750 cycle. See attached Trendplot.

```
DISCHARGE (AMP/HRS): 96.0/0.5
CHARGE (AMP/HRS): 64.0/1.0 TO SUM VOLTS OF 7.80 (108% rechg)
TRICKLE CHARGE FOR REMAINDER OF 1.00HRS @ 0.8A
```



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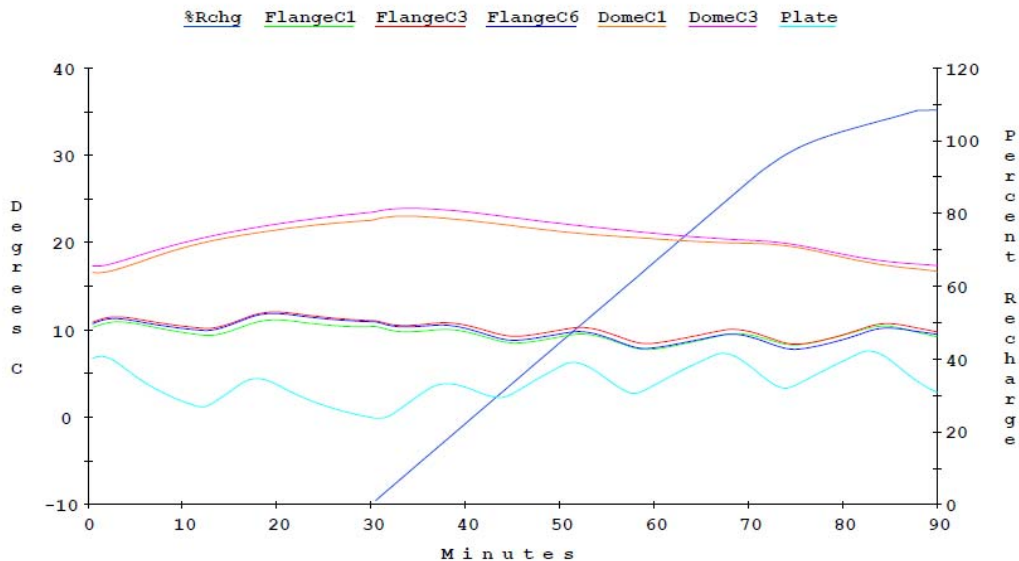
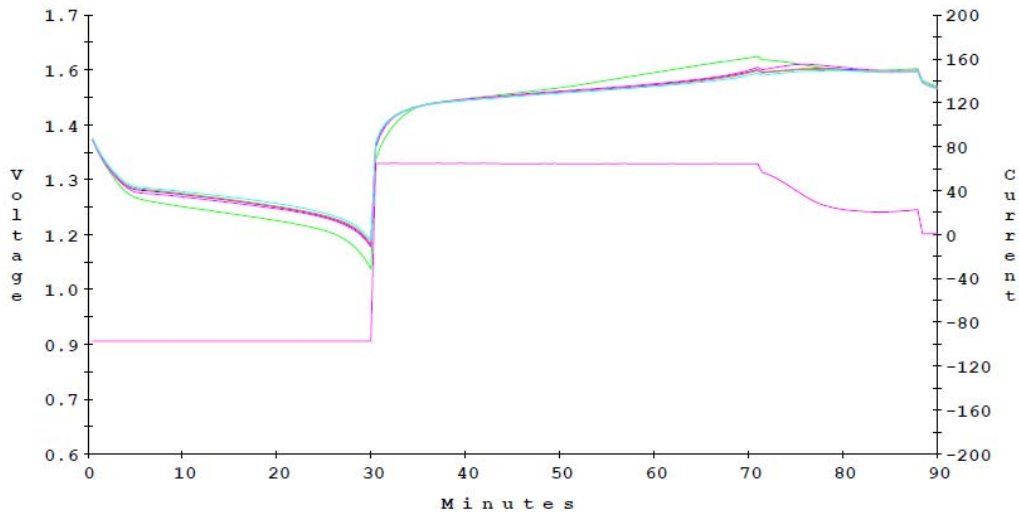
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### NSWC Crane (ISS) Pack ID 7605W 6 cells

Full Cycle Plot -- Cycle 11600 11-30-2009  
MFG: EP 81 A/H TEMP (C): 10 DOD (%): 60  
Cell 1 Cell 3 Cell 4 Cell 5 Cell 6 Curr





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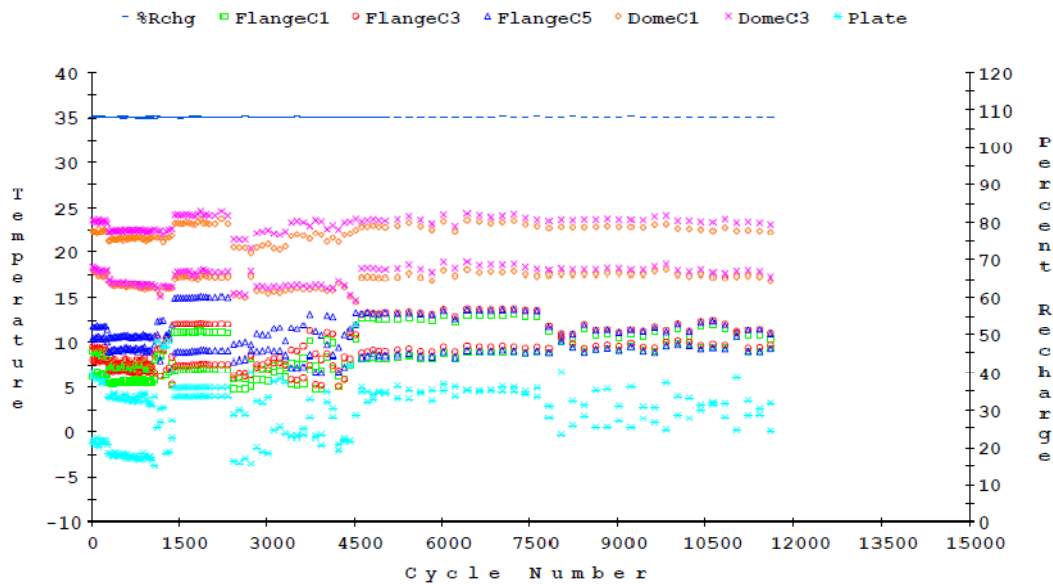
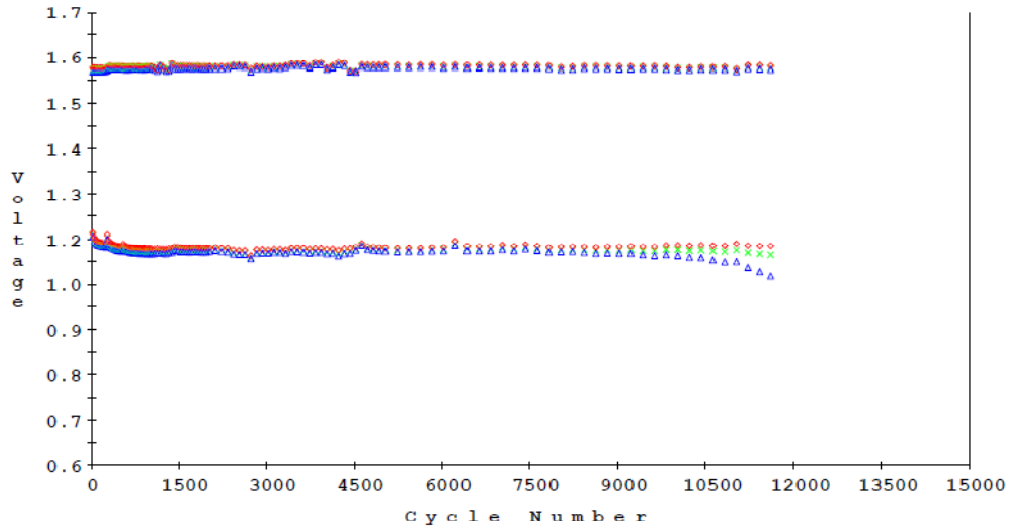
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NSWC Crane (ISS) Pack ID 7605W 6 cells  
Voltage/pressure/Recharge EOC/EOD Trend Plot 11-15-2007 - 12-01-2009  
MFG: EP TEMP (C): 10 DOD (%): 60  
x Vavg o Vmax Δ Vmin





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Wet Life Study Update:

Pack 7605W:

Cell Description: 5 ISS 81 Ah cells manufactured by Eagle-Picher and activated May 27, 1997.  
Loral/SS part #E005140-02.

Initial Evaluation: Completed 10/26/2007.

Life Cycle: Began 11/14/2007.

Test Conditions: LEO Stress test – 60% DOD, Orbit Period 90 minutes (30 minutes discharge, 60 minutes charge), @10°C. Charge control = VT.

Status: Completed 1750 cycle. See attached Trendplot.

DISCHARGE (AMP/HRS): 96.0/0.5  
CHARGE (AMP/HRS): 64.0/1.0 TO SUM VOLTS OF 7.80 (108% rechg)  
TRICKLE CHARGE FOR REMAINDER OF 1.00HRS @ 0.8A  
Cycle 1362. VT increased from 1.560 to 1.580 v/c due to low % rechg.  
Cycle 6691. VT increased from 1.580 to 1.590 v/c due to low EODV of cell #5.  
Cycle 6706. Increased % rechg trip from 108% to 110% due to low EODV cell #5.  
Cycle 6721. Increased % rechg trip from 110% to 112% due to low EODV cell #5.  
Cycle 6784. VT increased from 1.590 to 1.600 v/c due to low EODV of cell #5.  
Cycle 7221. Test regime changed from Stress to Mission profile- Dischg amps from 96.0 to 24.0;  
chg amps from 64.0 to 14.0; VT lowered from 1.600 to 1.520 v/c; %DOD lowered from 60 to 15%.  
Also test temp. lowered from 10 to 0 deg C.



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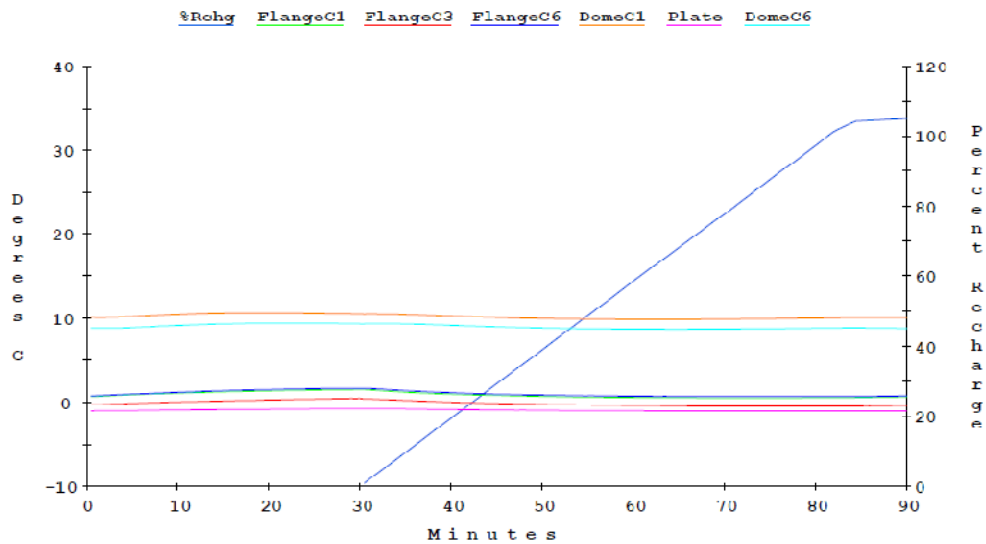
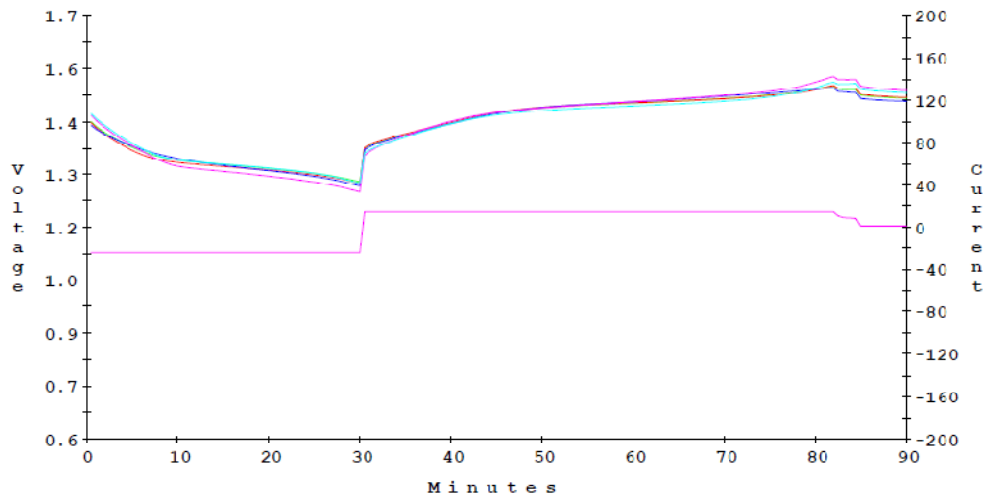
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NSWC Crane Pack ID 7606W 6 cells

Full Cycle Plot -- Cycle 8800 11-28-2009  
MFG: EPI 81 A/H TEMP (C): 10/0 changed cycle 7220 DOD (%): 60/15 changed cycle 7220  
Cell 1 Cell 2 Cell 3 Cell 5 Cell 6 Curr





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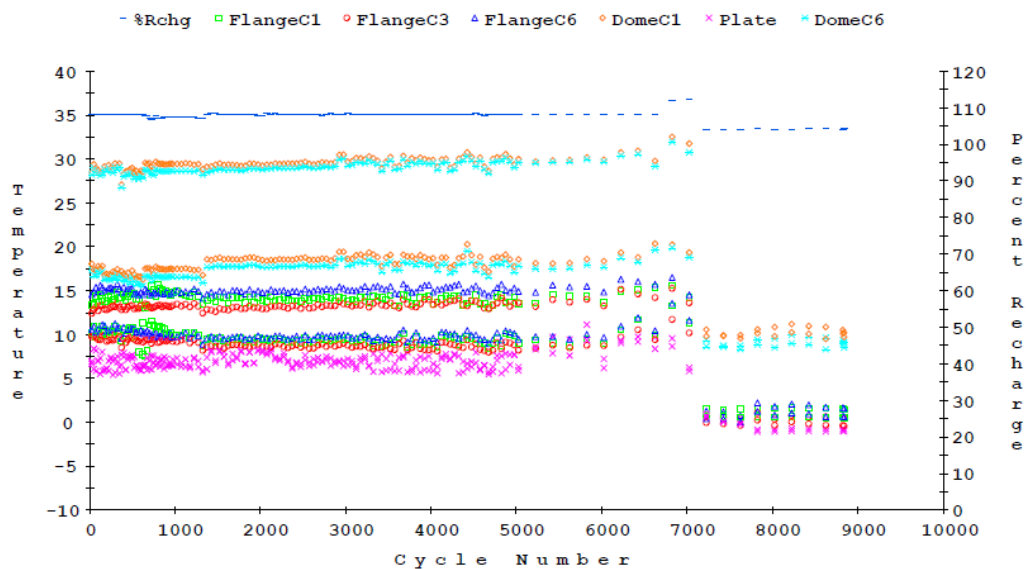
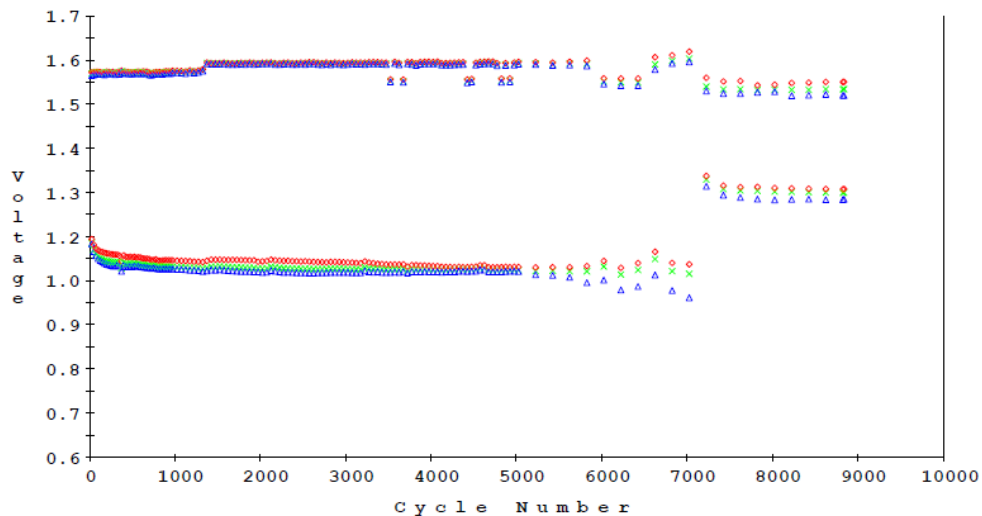
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NSWC Crane Pack ID 7606W 6 cells

Voltage/pressure/Recharge EOC/EOD Trend Plot 05-03-2008 - 12-01-2009  
MFG: EPI 81 A/H TEMP (C): 10/0 changed cycle 7220 DOD (%): 60/15 changed cycle 7220  
x Vavg o Vmax Δ Vmin



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